Raytheon
Santa Barbara Remote Sensing

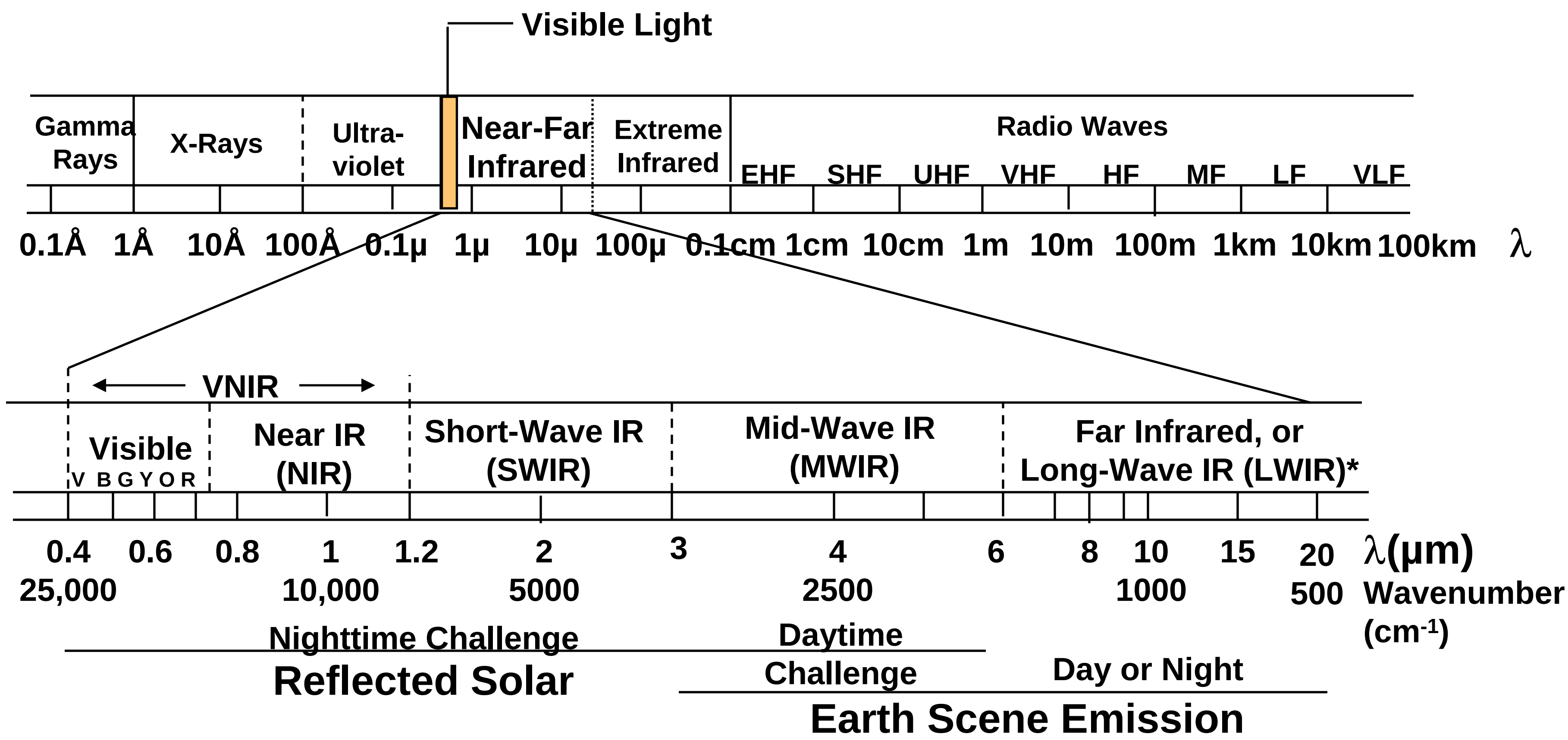
Passive Electro-optical Environmental Imaging

Carl F. Schueler

Presented at Naval Research Laboratory, Monterey CA 14 November 2003

Focus on Visible to Far Infrared

Raytheon
Santa Barbara Remote Sensing

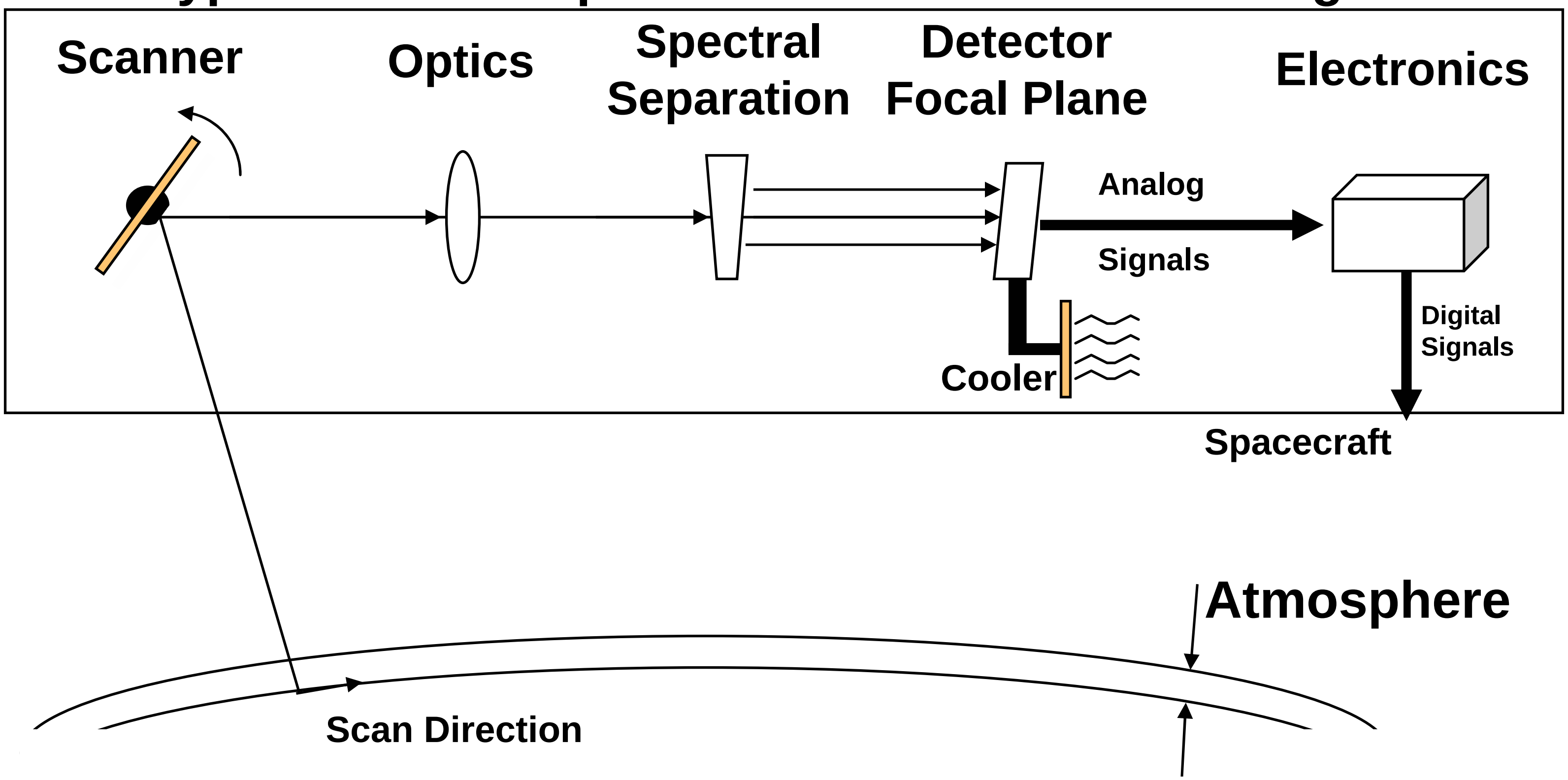


*Also known as Thermal IR (TIR)

Emitted or Reflected Radiance to Image Data

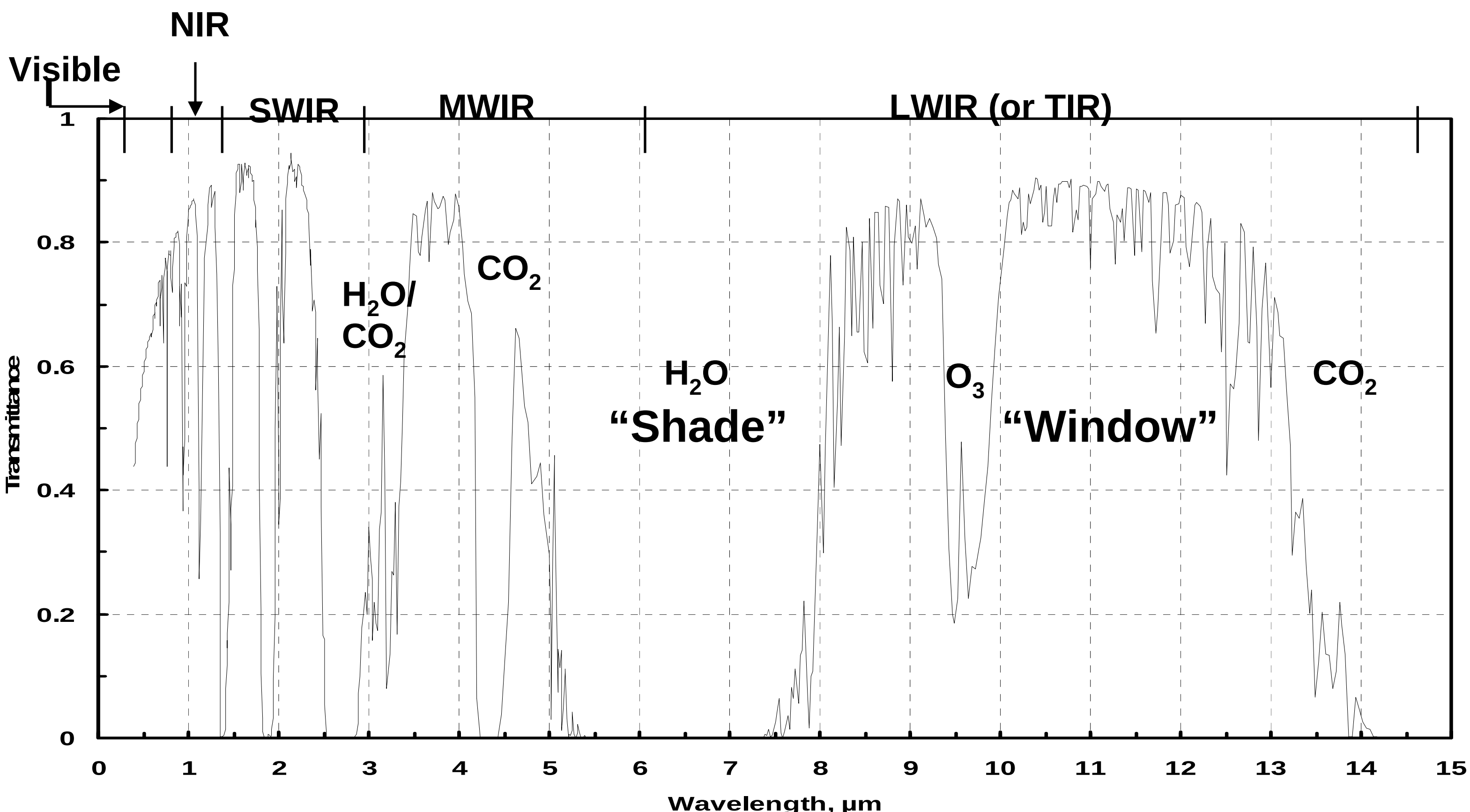
Raytheon
Santa Barbara Remote Sensing

Typical Electro-Optical Sensor Functional Design



Atmosphere "Shades" & "Windows" Guide Spectral Band Selection

Santa Barbara Remote Sensing



- **Clear Windows Selected for Surface Features**
- **Steep "Edges" Excellent for Atmospheric Sensing ("Sounding")**
- **Transmission Characteristics Caused by Gas Absorption (Main "Culprits" Shown)**

MODTRAN standard Atmosphere
Dr. Paul Lommen, SBRS

Topics to be Discussed

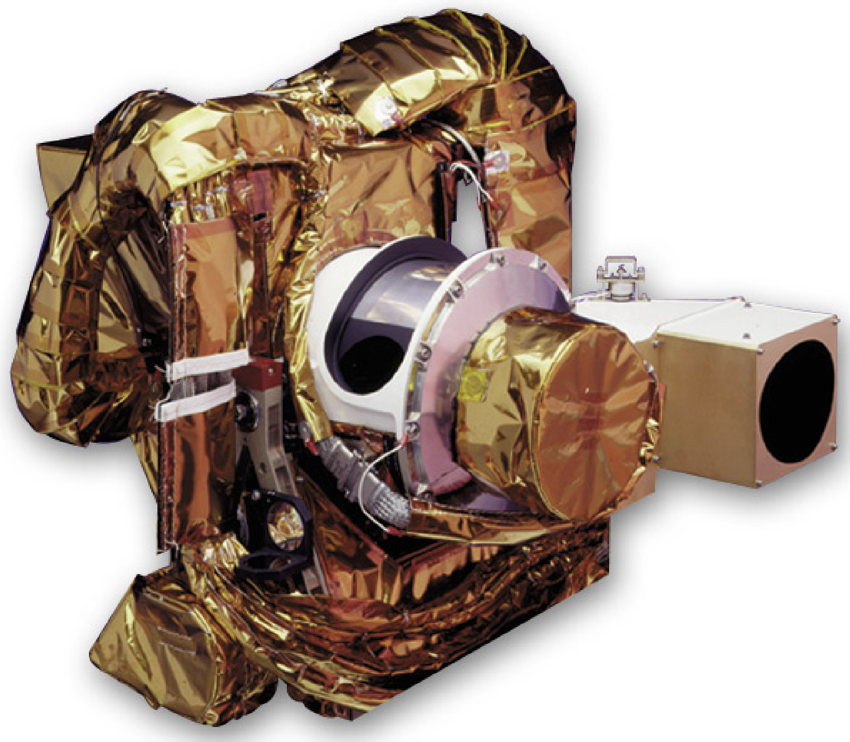
Santa Barbara Remote Sensing

- Overview of recent environmental sensors
  - Sea-Viewing Wide Field-of-View Sensor (SeaWiFS) - 1993
  - Tropical Rainfall Measuring Mission (TRMM) Visible Infrared Scanner (VIRS) - 1997
  - NASA Earth Observing System MODerate-resolution Imaging Spectroradiometer (MODIS) - 1999
  - National Polar-orbiting Operational Environmental Satellite System (NPOESS). Visible Infrared Imaging Radiometer Suite (VIIRS) – in development
- Methodology to define sensor specification from user needs
- Compare AVHRR/DMSP OLS and VIIRS Spatial Resolution
- Fundamental sensor design issue: Spatial resolution vs. Sensitivity for Feature identification

Sea-viewing Wide Field-of-view Sensor (SeaWiFS)

Raytheon
Santa Barbara Remote Sensing

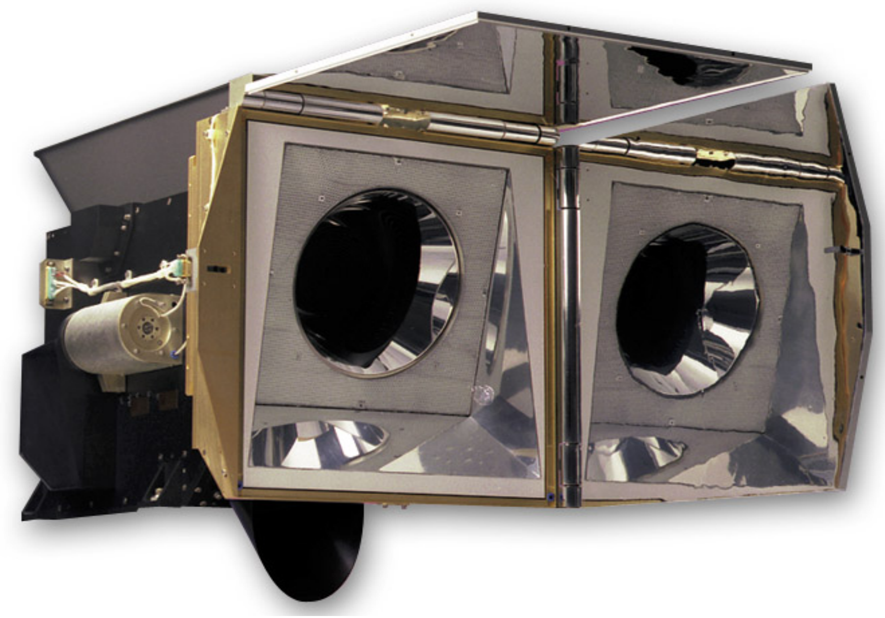
- Delivered December 1993/Launched 4 September 1997
- Orbit: 705km noon polar sun-synchronous
- 1.13 km nadir geometric instantaneous field of view (GIFOV)
- Off-axis, afocal 7.6 cm aperture rotating telescope, focusing aft optics
- 360 rpm telescope cross-track scan
- Sun glint avoidance via commandable +/- 20 degree sensor fore-aft tilt
- 22 kg scanner/24 kg electronics box
- 51 x 51 x 51 cm
- Eight spectral bands 0.4-0.885 um
- 670-950 Signal-to-noise ratio for ocean reflectance measurements
- On-board solar diffuser calibration update reference



Tropical Rainfall Measuring Mission (TRMM) Visible Infrared Scanner (VIRS)

Raytheon
Santa Barbara Remote Sensing

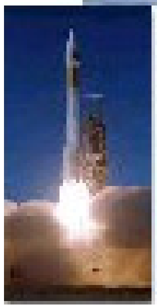
- Launched 27 November 1997
- Orbit: 350km equatorial 35 degree inclination
- 2km nadir GIFOV
- 2-mirror Cassegrain 9 cm aperture telescope
- Cross-track “paddle” scan mirror (similar to MODIS scan design)
- 24 kg scanner/13 kg electronics box
- 43 x 80 x 46 cm scanner dimensions
- 5 (AVHRR) spectral bands 0.63-12 um
- Excellent SNR and NEdT for cloud analyses via passive radiative cooling
- On-board calibration update references:
  - Solar diffuser for reflective bands
  - Blackbody for emissive bands



MODerate-resolution Imaging Spectroradiometer (MODIS)

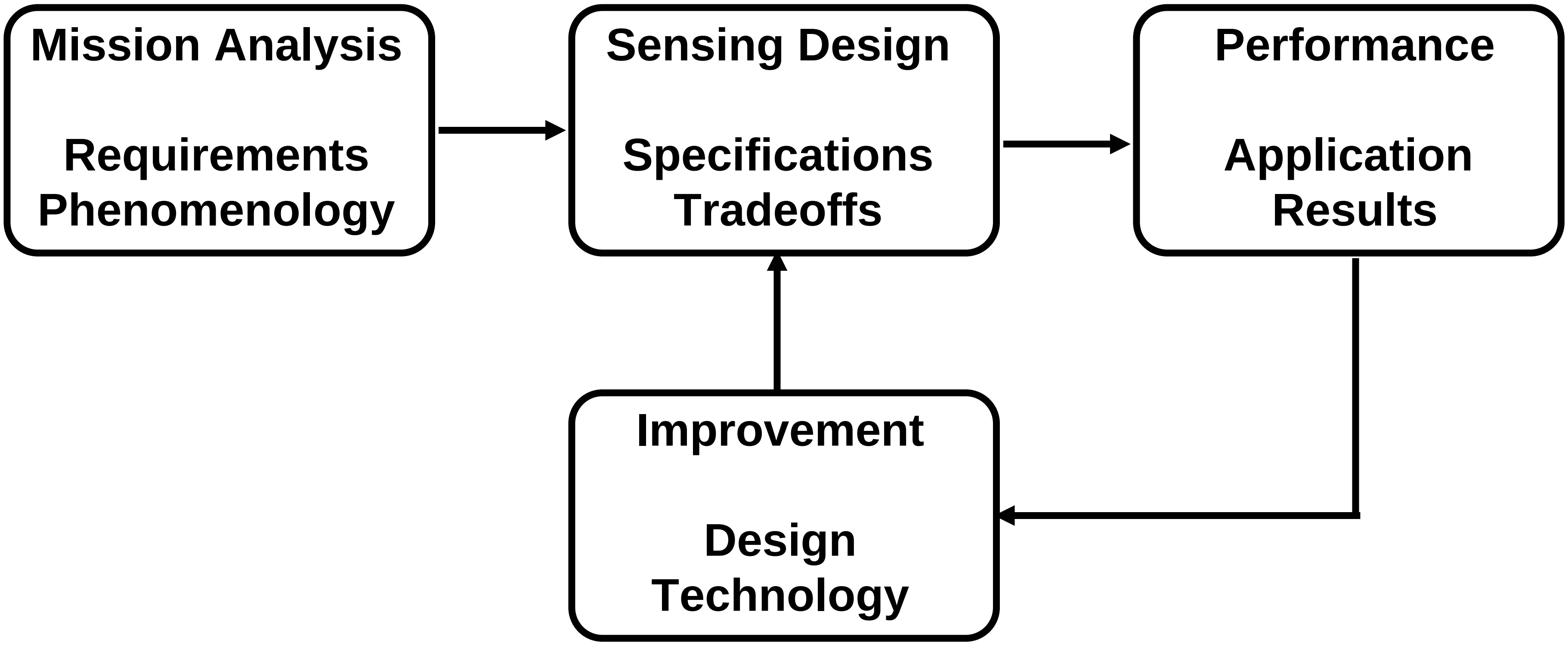
Raytheon
Santa Barbara Remote Sensing

- First launched 18 December 1999 on NASA's EOS Terra spacecraft
- Orbit: 705km polar sun-synchronous 2230 ascending (& Aqua 1330 ascending)
- Nadir GIFOVs: 250m in 2 vis bands; 500m in 5 VNIR bands; 1km in 29 VNIR-LWIR bands
- Off-axis, afocal with intermediate field stop and focusing refractive aft optics
- 20 rpm cross-track "paddle" scan mirror
- 250 kg scanner/electronics package
- 100 x 160 x 100 cm
- Excellent SNR and NEdT for atmosphere, land, and ocean analyses via passive radiative cooling
- On-board calibration update references:
  - Solar diffuser and stability monitor for reflective bands
  - Blackbody for emissive bands
  - Space and lunar views
  - Spectroradiometric calibration assembly for spectral band registration and center updates



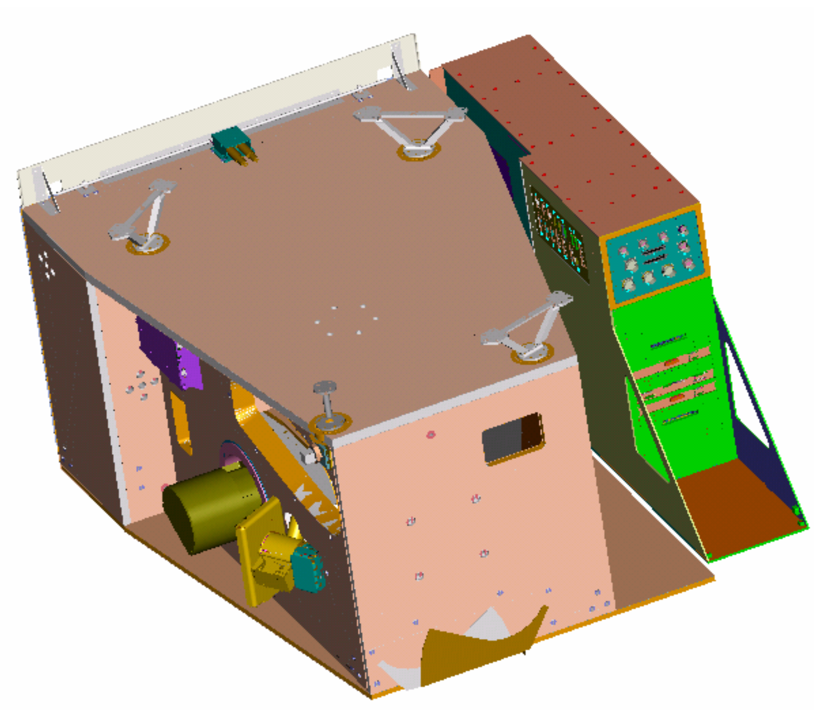
User Needs Drove Design

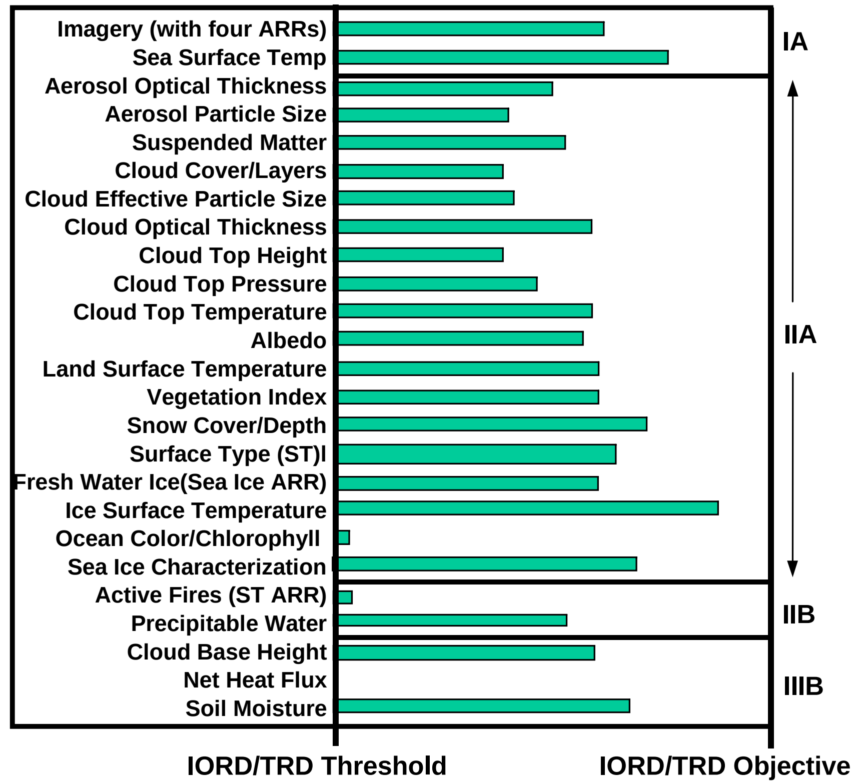
Raytheon
Santa Barbara Remote Sensing



VIIRS Provides Environmental Data Records (EDRs)

Raytheon
Santa Barbara Remote Sensing

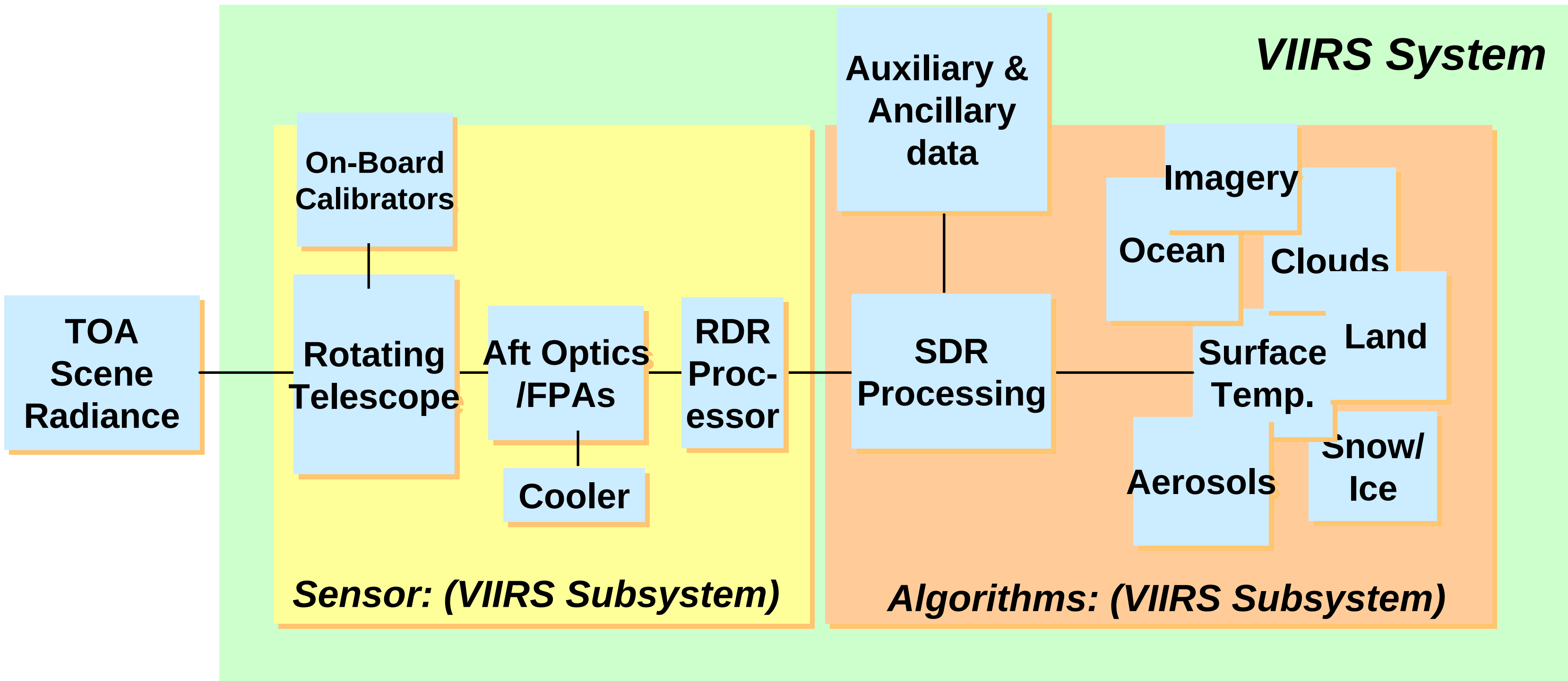




- Visible Infrared Imaging Radiometer Suite (VIIRS) System Design based on integrated Sensor and Algorithms
- Engineering Development Unit (EDU) approaching integration at SBRS
- EDR Science Algorithms developed, documented, and publicly released Spring 2002 by Raytheon Technical Services Company (RTSC) Information Technology and Scientific Services (ITSS)

EDR Performance Verified by Hardware & Testbed

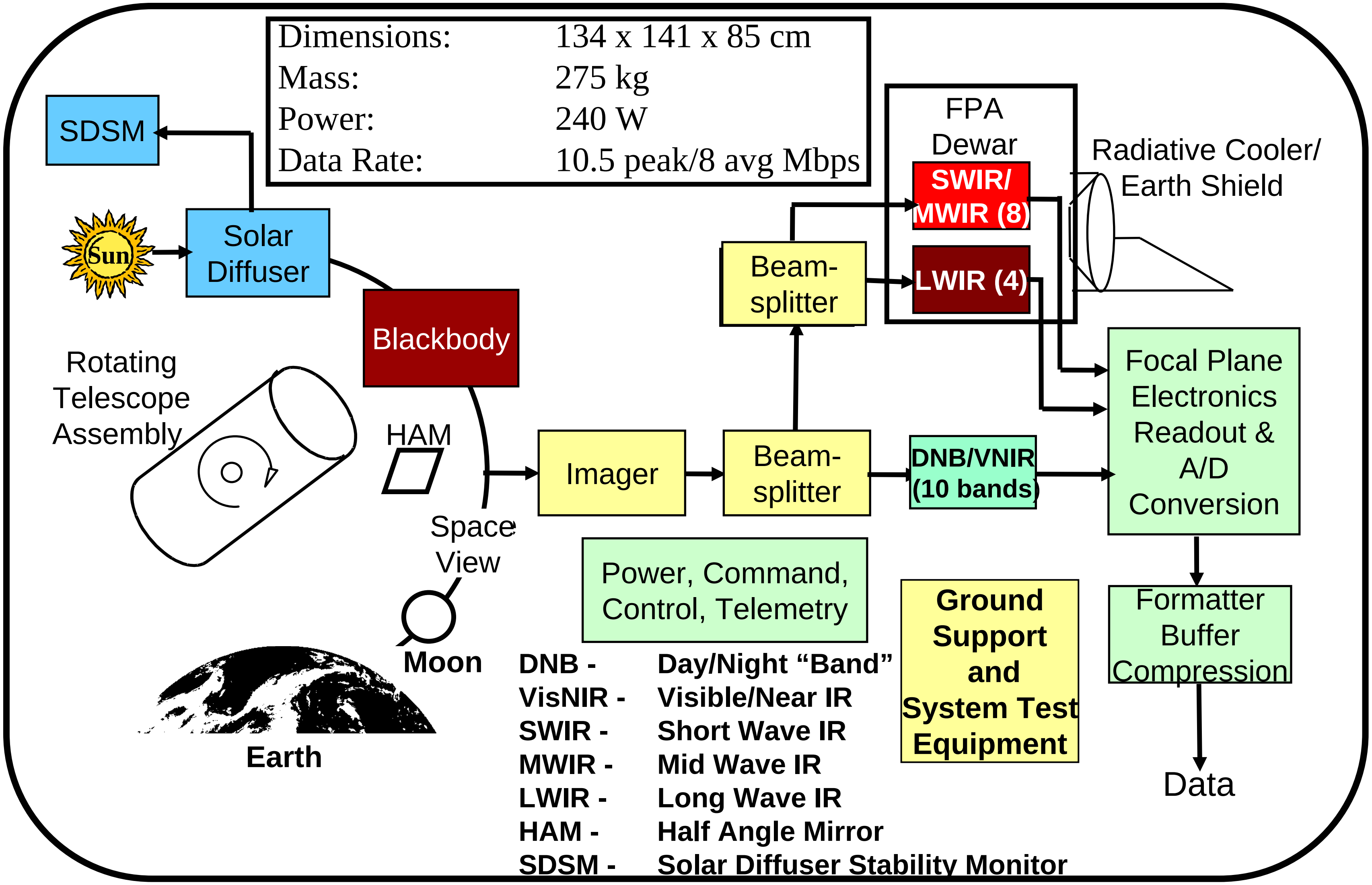
Raytheon
Santa Barbara Remote Sensing



- EDRs drive algorithm and raw sensor data requirements
- Sensor specification derived from EDRs with testbed
- Sensor performance verified by hardware risk-reduction demonstrations and analyses
- EDR performance verified by testbed with sensor models

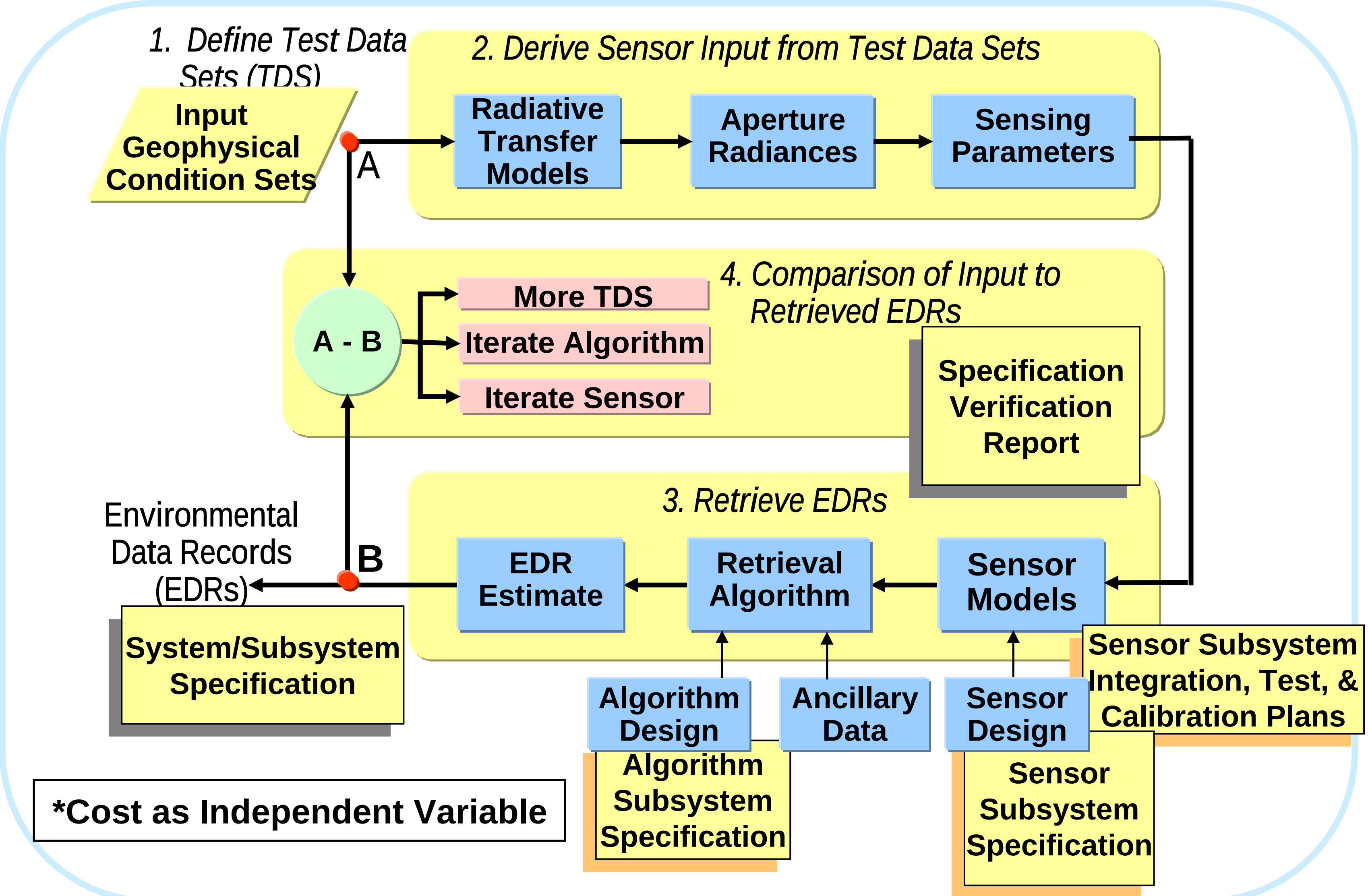
Photons to Digital Data: VIIRS Architecture Stable Since PDR

Raytheon
Santa Barbara Remote Sensing



Testbed-based CAIV* Trades For "Best Value" Optimization

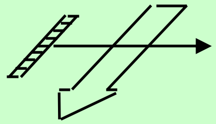
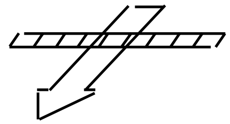
Raytheon
Santa Barbara Remote Sensing



*Cost as Independent Variable

CAIV Trades For Best Value
Single Sensor Configuration

Raytheon
Santa Barbara Remote Sensing

	Whiskbroom	Pushbroom
		
	~7 km/second Ground Speed (Spacecraft Provides In-Track Scan)	
Focal Plane	**Several Detectors In-track per Band**	**Line Array Cross-track per Band**
Example	**ETM, MODIS,** ***VIIRS Scanner***	**EO-1, SPOT** ***VIIRS DNB option***

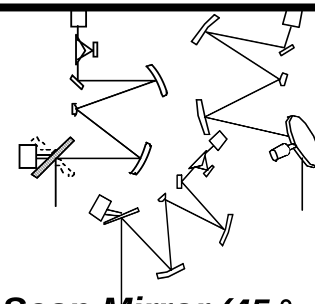
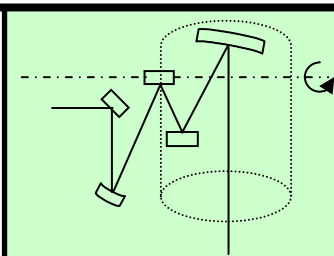
3

1

- ± 55.8° FOV
- Cold FPAs

2 **<Cost**

Integral Ocean Color
- **Lower cost per platform**
- **Co-Registered Ocean Color bands improve other EDRs**
- **Wider Ocean Color swath**

Whiskbroom Scan Approach	 ***Scan Mirror (45 °,*** **compound, paddle)**	 ***RotatingTelescope (SeaWiFS)***
Assets	**Lower Inertia**	**Straight Scan Line** **Straightforward baffle design** **Allows Integral DNB**
Liabilities	**Require Spacecraft Glare Shield in Terminator orbit**	**Inertia requires constant scan rate**

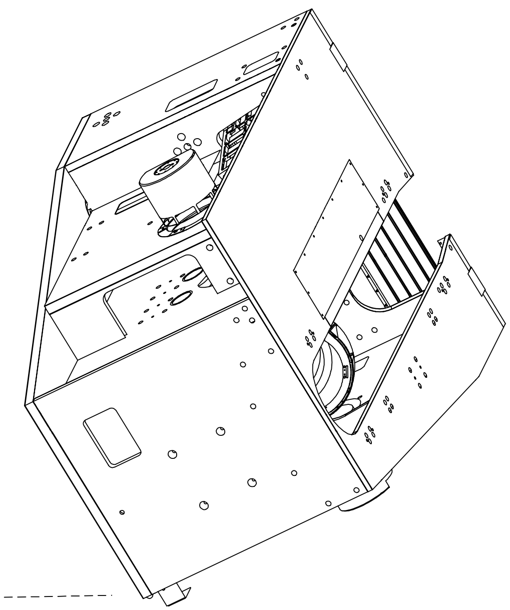
Solar intrusion in Terminator orbit: Rotating Telescope Design Driver

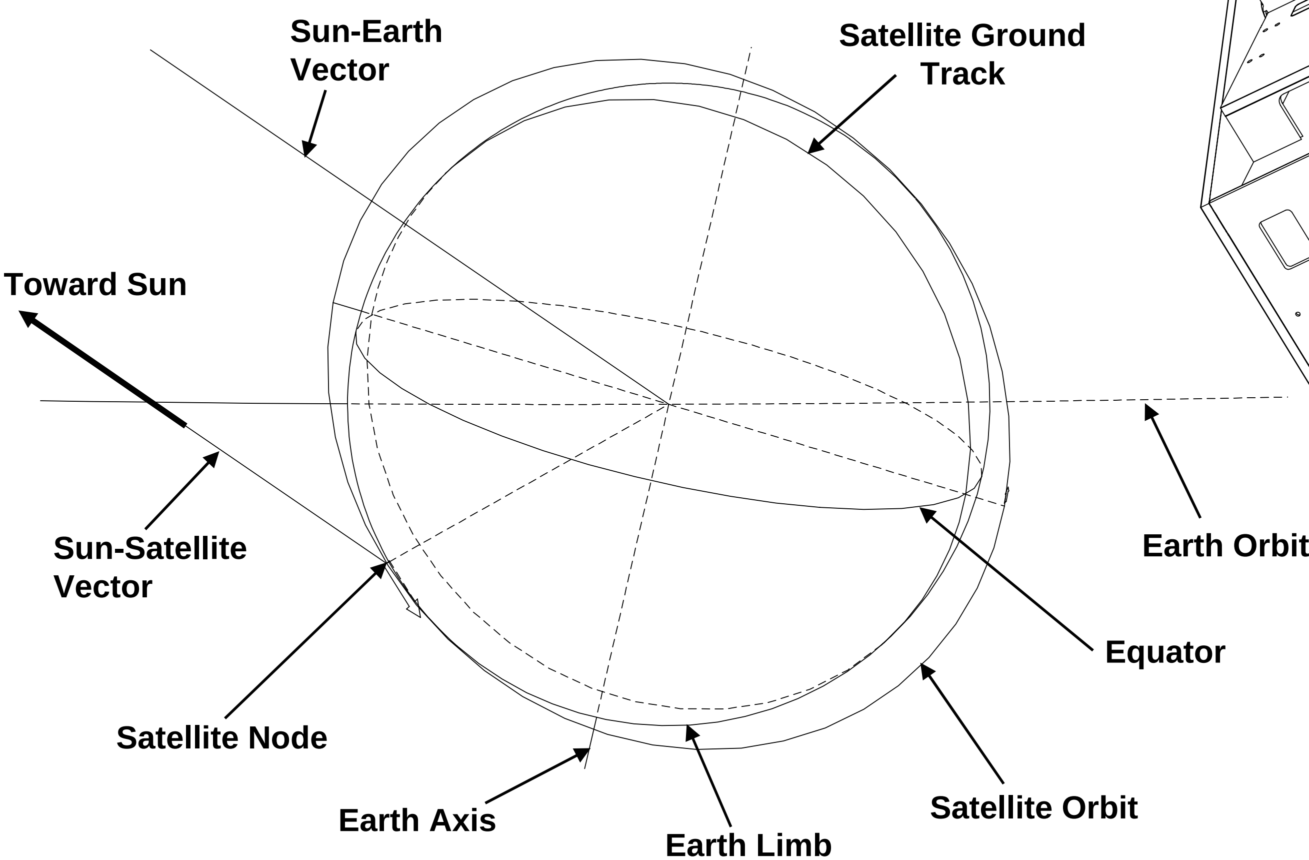
Raytheon
Santa Barbara Remote Sensing

Terminator Orbit, Beta = 63 deg

Satellite Position: 10 minutes Prior to Max Solar Exposure

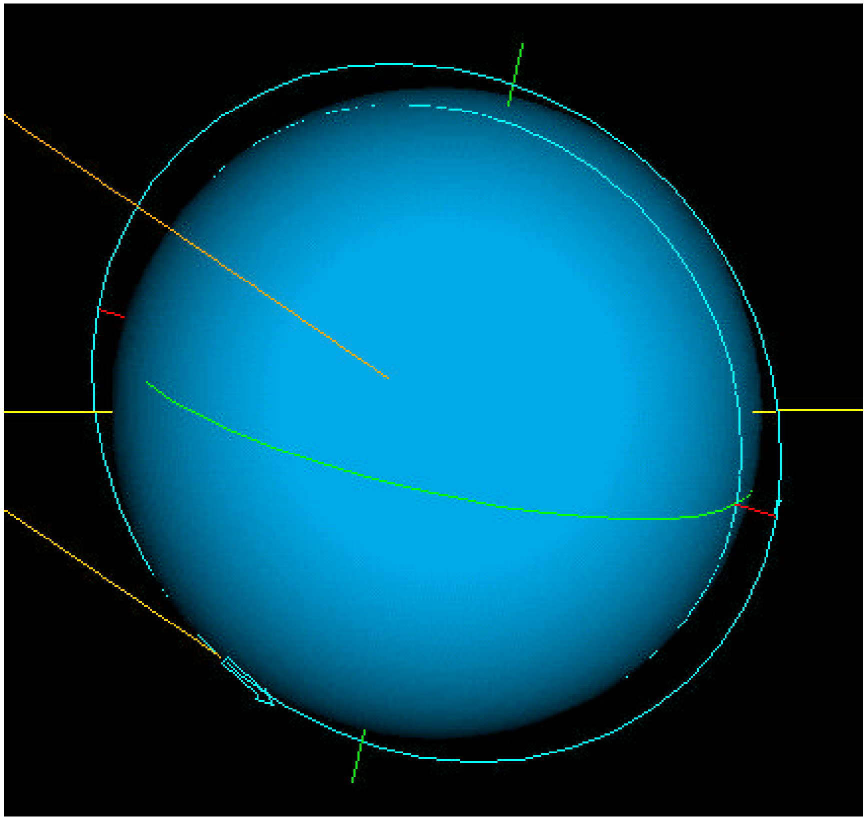
Direct View of Sensor from the Sun





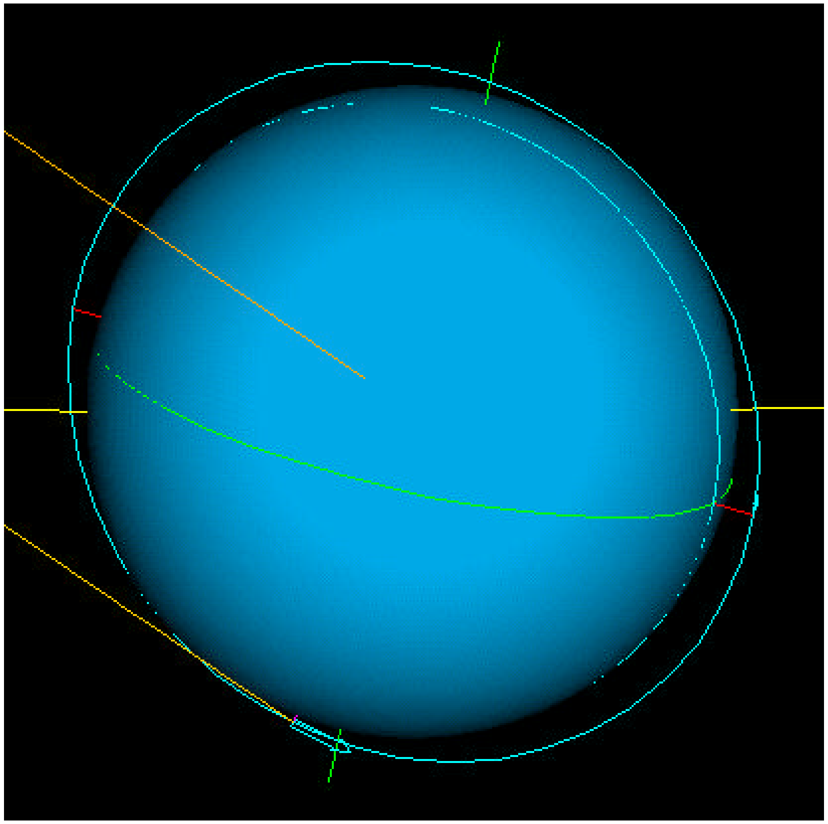
Satellite Position: 5 minutes Prior to Max Solar Exposure

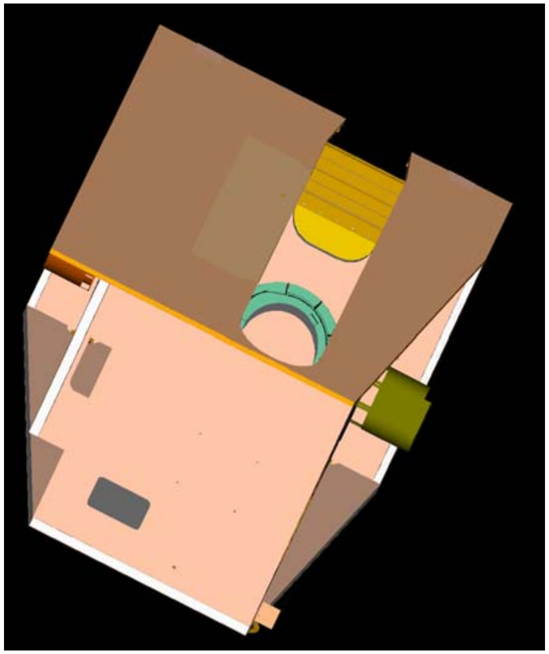
Raytheon
Santa Barbara Remote Sensing



Satellite Position: During Max Solar Exposure

Raytheon
Santa Barbara Remote Sensing



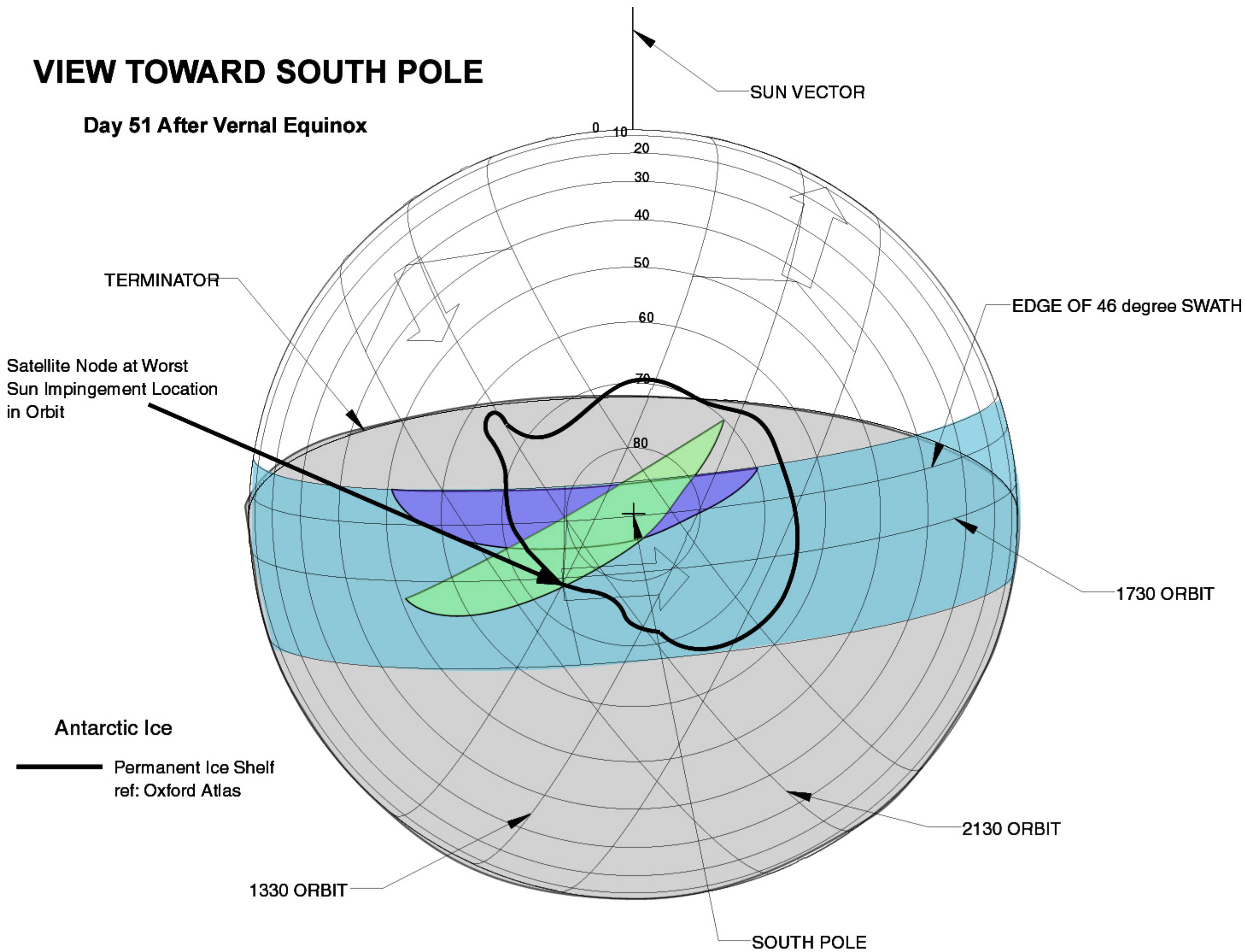


Sensor Provides Optimum Coverage in Terminator Orbits

Raytheon
Santa Barbara Remote Sensing

Baffled telescope has low sensitivity to far field glare and solar impingement

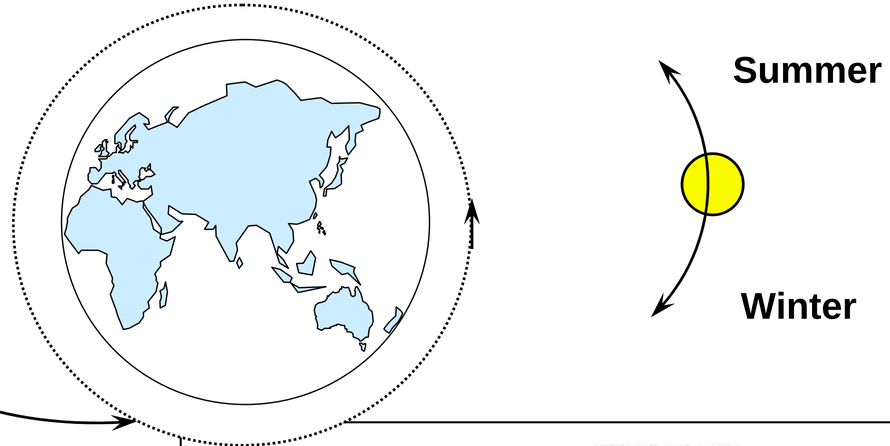
Data available from preceding orbit and/or Sensors in mid-day orbits can fill-in gap

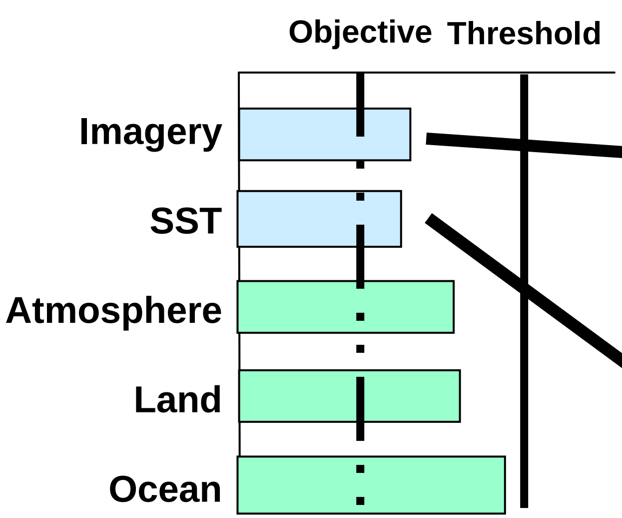


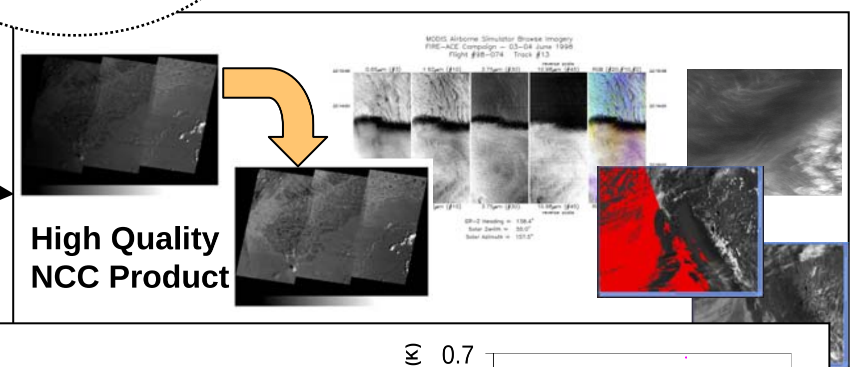
EDR Performance Optimized Over Environmental Conditions

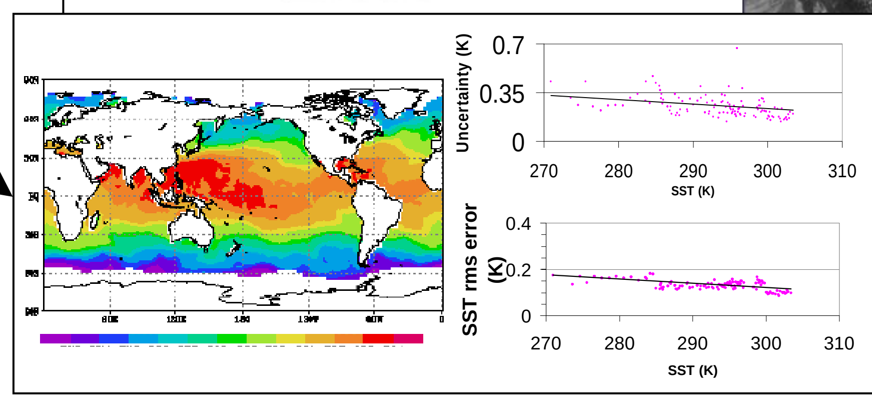
Raytheon
Santa Barbara Remote Sensing

Attributes Stratified
- **By Geographic Region**
- **Seasonally**
- **Over Measurement Range**









Iterative Process to Verified System/Subsystem Specification

Raytheon
Santa Barbara Remote Sensing

Verification ⟷ Flowdown

SRD → **Algorithm/ Sensor teams**: **EDR Spec (28+)*** → **Algorithm team**: **Algorithm Data Definition**** → **Sensor team**: **Sensor Performance Requirements***** → Sensor Module Specifications

Algorithm/ Sensor teams — EDR Spec (28+)*

- **HCS/HRI/VCS/VRI**
- **Hor/Vert Coverage**
- **Measurement Range**
- **Meas Accy/Prec/Unc**
- **Long-term Stability**
- **Mapping Uncertainty**
- **Min Swath Width**

*VIIRS System Specification
*System Verification and Validation Plan

Algorithm team — Algorithm Data Definition**

- **Bands CW/BW & Tolerances**
- **Bandpass Shape**
- **Dynamic Range/Sensitivity**
- **Rdmtrc Accuracy/Stability**
- **Horzntl Smplg Interval (HSI)**
- **Spatial Resolution (MTF)**
- **Band Co-Registration**
- **Polarization**
- **Geolocation**
- **Auxiliary/Ancillary Data**

**Algorithm Data Definition (ADD) Documents (Y2371-- Y2384)

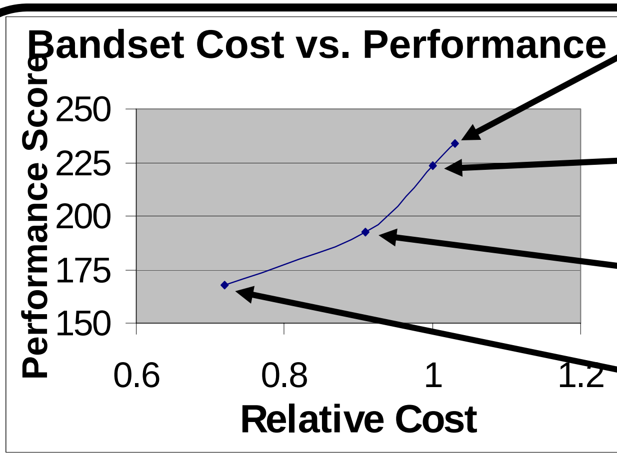
Sensor team — Sensor Performance Requirements***

- **Scan Definition**
- **Calibration Definition**
- **IFOV/Response Uniformity**
- **Crosstalk**
- **Stray Light Rejection**
- **LOS Pointing/Jitter Rqmnts**
- **CW/BW tolerance**
- **Spectral Uniformity**
- **Out-of-Band Rejection**

***Performance and Specification Verification Report

Robust Spectral Capability with Science Bonus

Raytheon
Santa Barbara Remote Sensing

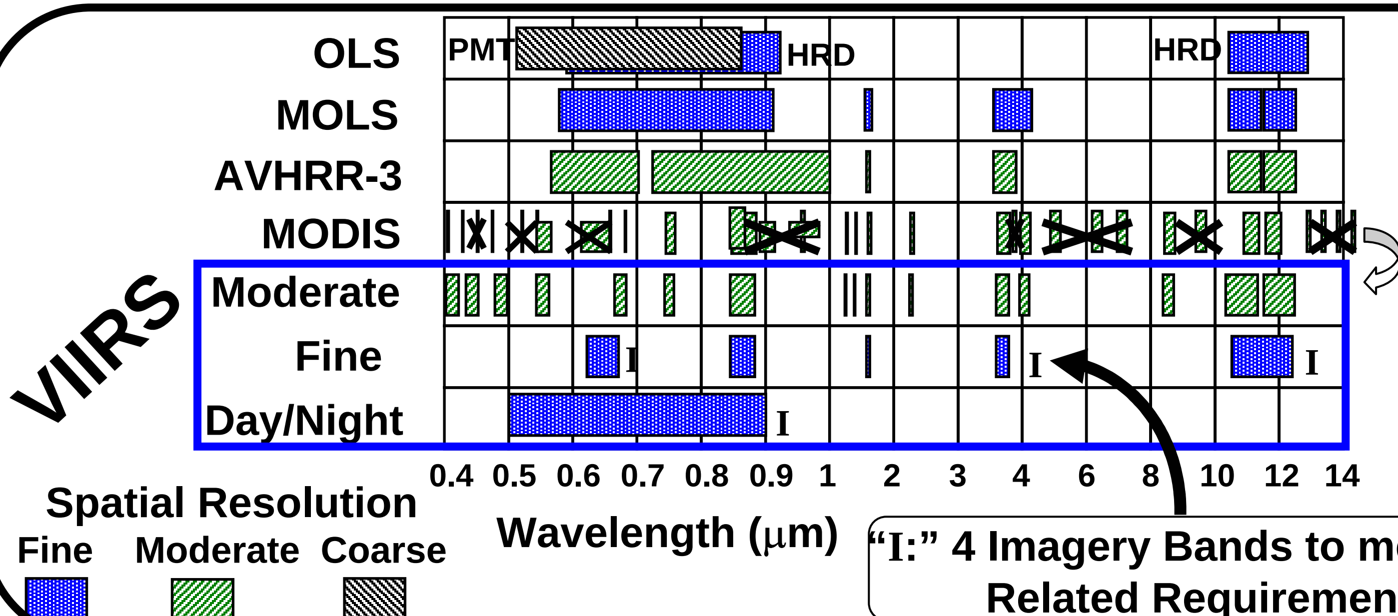


4. 22 Bands: 17 + Fine NDVI + Fine Snow + Aerosol + 2 Cloud
dUtility/dCost ~ 1 + "Bonus" Fine SRD HCSs

3. 17 Bands: 11 + 4 Ocean color + Aerosol + Cloud
Utility/Cost > 1

2. 11 Bands: 8 + Snow + NDVI + Aerosol + 3rd focal plane
Need Ocean Color Bands to Approach Threshold

1. 8 Bands: DNB + (3 Imaging + 4 SST)/2 focal planes
Meet Imagery/SST but few Category IIA Thresholds



36 - 20
= 16
+ 5
+ 1 = <u>*22*</u>

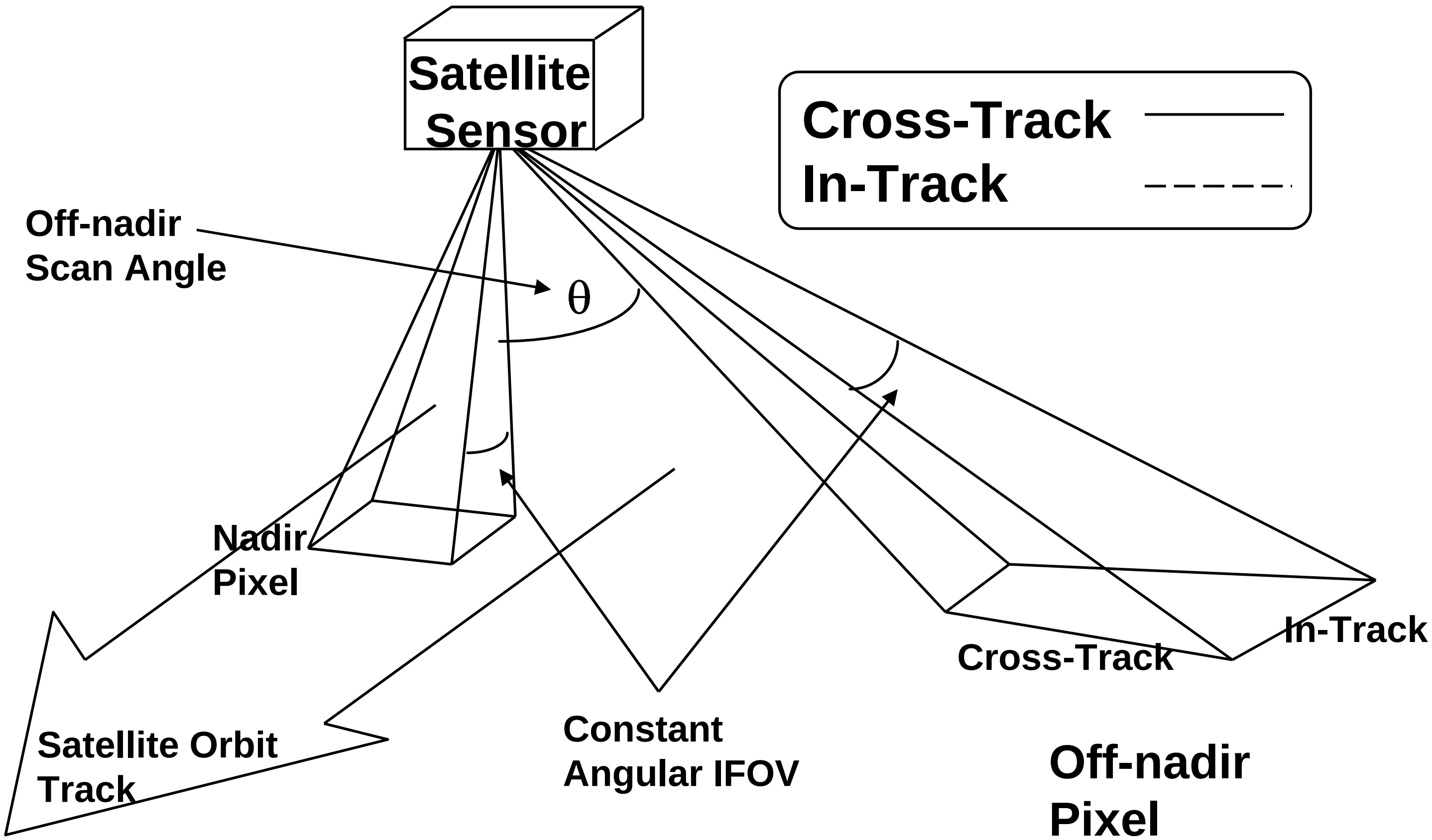
"I:" 4 Imagery Bands to meet Application Related Requirements Thresholds

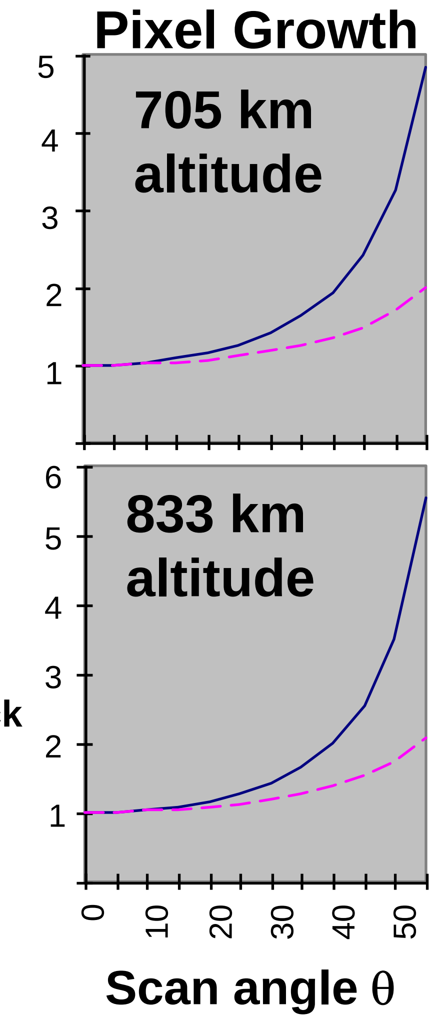
Spectral, Spatial, & Radiometric Attributes of 22 VIIRS Bands

Raytheon
Santa Barbara Remote Sensing

		Band No.	Wave-length (μm)	Horiz Sample Interval (km Downtrack x Crosstrack)		Driving EDRs	Radi-ance Range	Ltyp or Ttyp	Signal to Noise Ratio (dimensionless) or NEΔT (Kelvins)		
				Nadir	End of Scan				Required	Predicted	Margin
VIS/NIR FPA	Silicon PIN Diodes	M1	0.412	0.742 x 0.259	1.60 x 1.58	Ocean Color	Low	44.9	352	441	25%
						Aerosols	High	155	316	807	155%
		M2	0.445	0.742 x 0.259	1.60 x 1.58	Ocean Color	Low	40	380	524	38%
						Aerosols	High	146	409	926	126%
		M3	0.488	0.742 x 0.259	1.60 x 1.58	Ocean Color	Low	32	416	542	30%
						Aerosols	High	123	414	730	76%
		M4	0.555	0.742 x 0.259	1.60 x 1.58	Ocean Color	Low	21	362	455	26%
						Aerosols	High	90	315	638	102%
		I1	0.640	0.371 x 0.387	0.80 x 0.789	Imagery	Single	22	119	146	23%
		M5	0.672	0.742 x 0.259	1.60 x 1.58	Ocean Color	Low	10	242	298	23%
						Aerosols	High	68	360	522	45%
		M6	0.746	0.742 x 0.776	1.60 x 1.58	Atmospheric Corr'n	Single	9.6	199	239	20%
		I2	0.865	0.371 x 0.387	0.80 x 0.789	NDVI	Single	25	150	225	50%
		M7	0.865	0.742 x 0.259	1.60 x 1.58	Ocean Color	Low	6.4	215	388	81%
						Aerosols	High	33.4	340	494	45%
CCD		DNB	0.7	0.742 x 0.742	0.742 x 0.742	Imagery	Var.	6.70E-05	6	5.7	-5%
S/MWIR	PV HgCdTe (HCT)	M8	1.24	0.742 x 0.776	1.60 x 1.58	Cloud Particle Size	Single	5.4	74	98	32%
		M9	1.378	0.742 x 0.776	1.60 x 1.58	Cirrus/Cloud Cover	Single	6	83	155	88%
		I3	1.61	0.371 x 0.387	0.80 x 0.789	Binary Snow Map	Single	7.3	6.0	97	1523%
		M10	1.61	0.742 x 0.776	1.60 x 1.58	Snow Fraction	Single	7.3	342	439	28%
		M11	2.25	0.742 x 0.776	1.60 x 1.58	Clouds	Single	0.12	10	17	66%
		I4	3.74	0.371 x 0.387	0.80 x 0.789	Imagery Clouds	Single	270 K	2.500	0.486	415%
		M12	3.70	0.742 x 0.776	1.60 x 1.58	SST	Single	270 K	0.396	0.218	82%
		M13	4.05	0.742 x 0.259	1.60 x 1.58	SST	Low	300 K	0.107	0.063	69%
						Fires	High	380 K	0.423	0.334	27%
LWIR	PV HCT	M14	8.55	0.742 x 0.776	1.60 x 1.58	Cloud Top Properties	Single	270 K	0.091	0.075	22%
		M15	10.763	0.742 x 0.776	1.60 x 1.58	SST	Single	300 K	0.070	0.038	85%
		I5	11.450	0.371 x 0.387	0.80 x 0.789	Cloud Imagery	Single	210 K	1.500	0.789	90%
		M16	12.013	0.742 x 0.776	1.60 x 1.58	SST	Single	300 K	0.072	0.051	42%

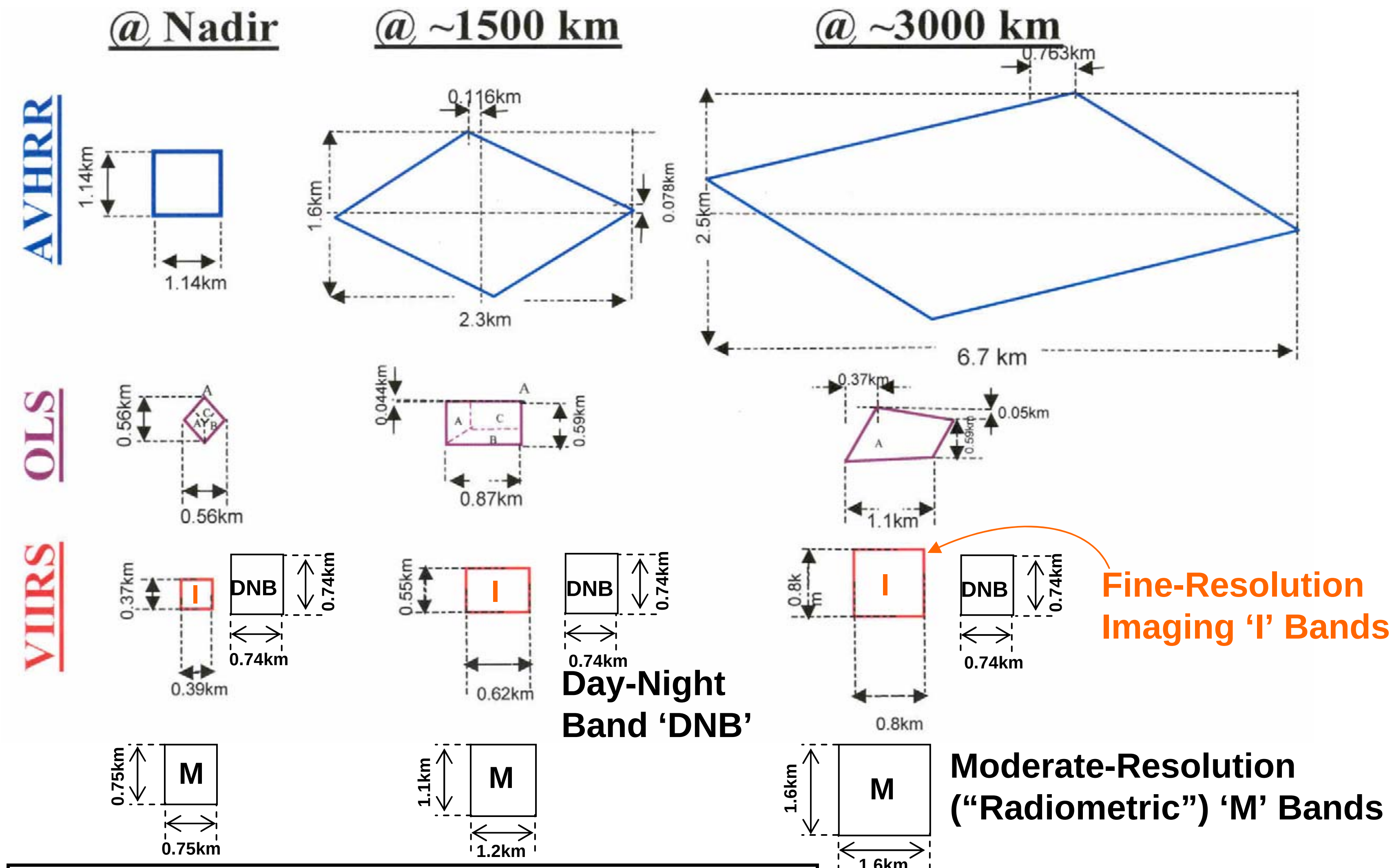
Nadir to Edge of Scan Pixel Growth





Finer Sampling, Spatial Resolution & Better Sensitivity

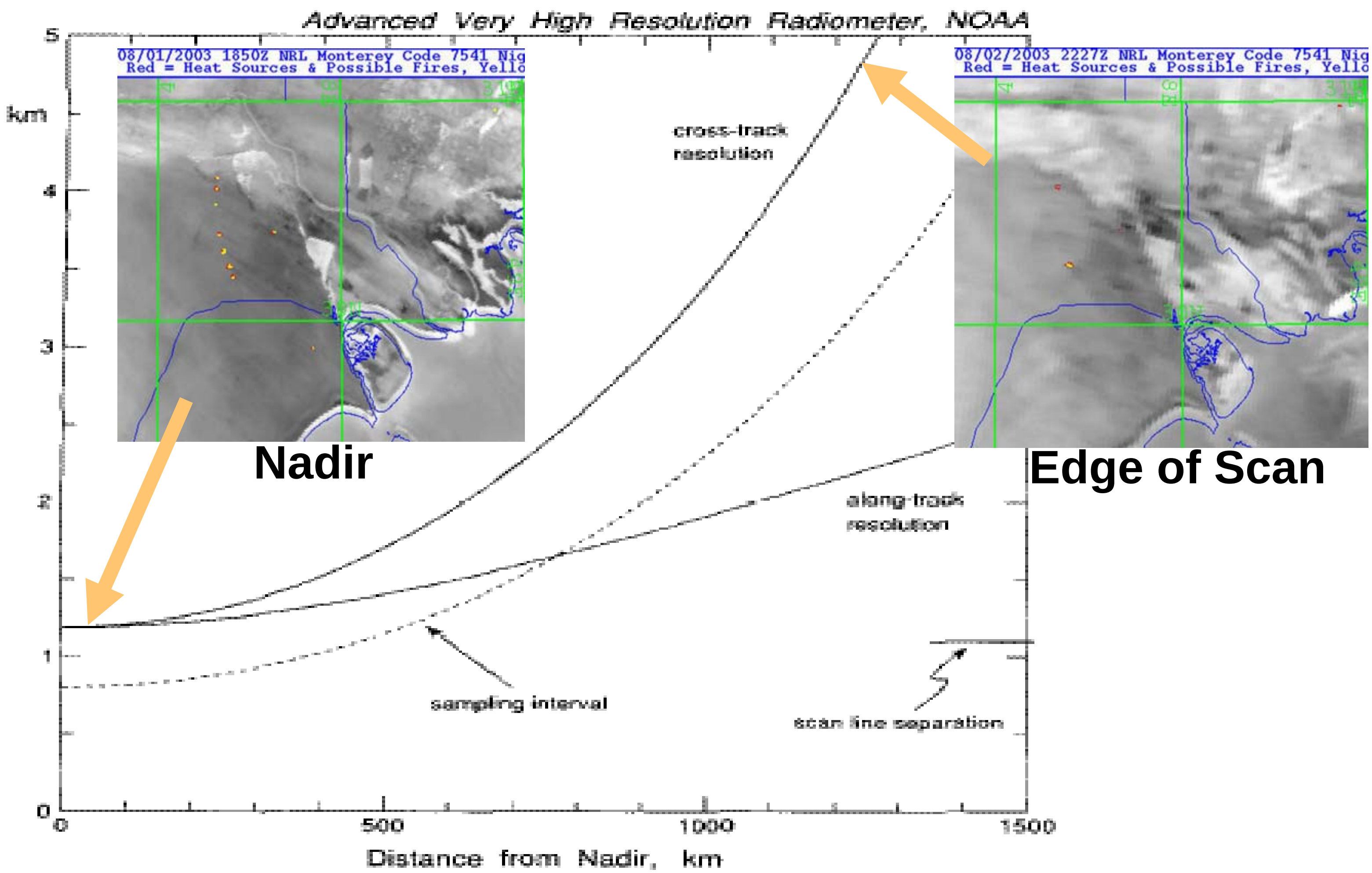
Raytheon
Santa Barbara Remote Sensing



SNR predicted and specified at worst-case edge of scan:
~60% better nadir SNR *and* finer spatial resolution

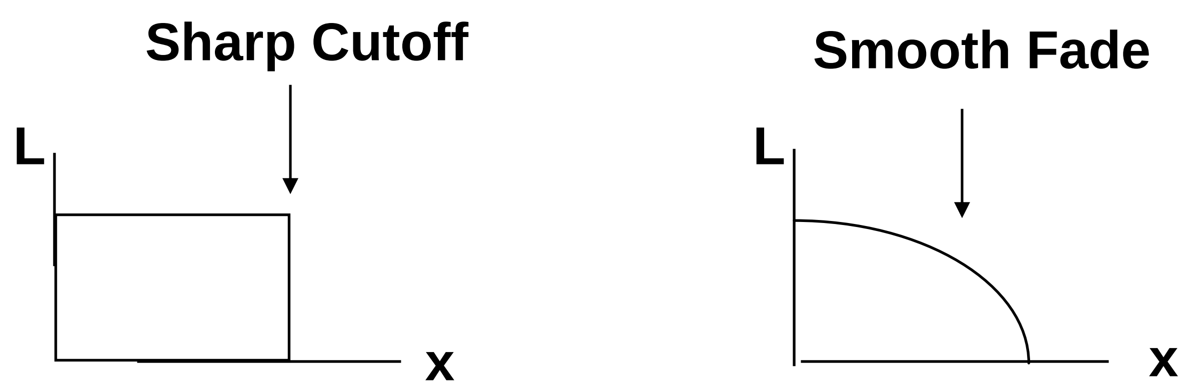
AVHRR Scan Geometry: Nadir & Edge of Scan

Raytheon
Santa Barbara Remote Sensing



Spatial Frequency Concept: Powerful, Practical Design Tool

Raytheon
Santa Barbara Remote Sensing



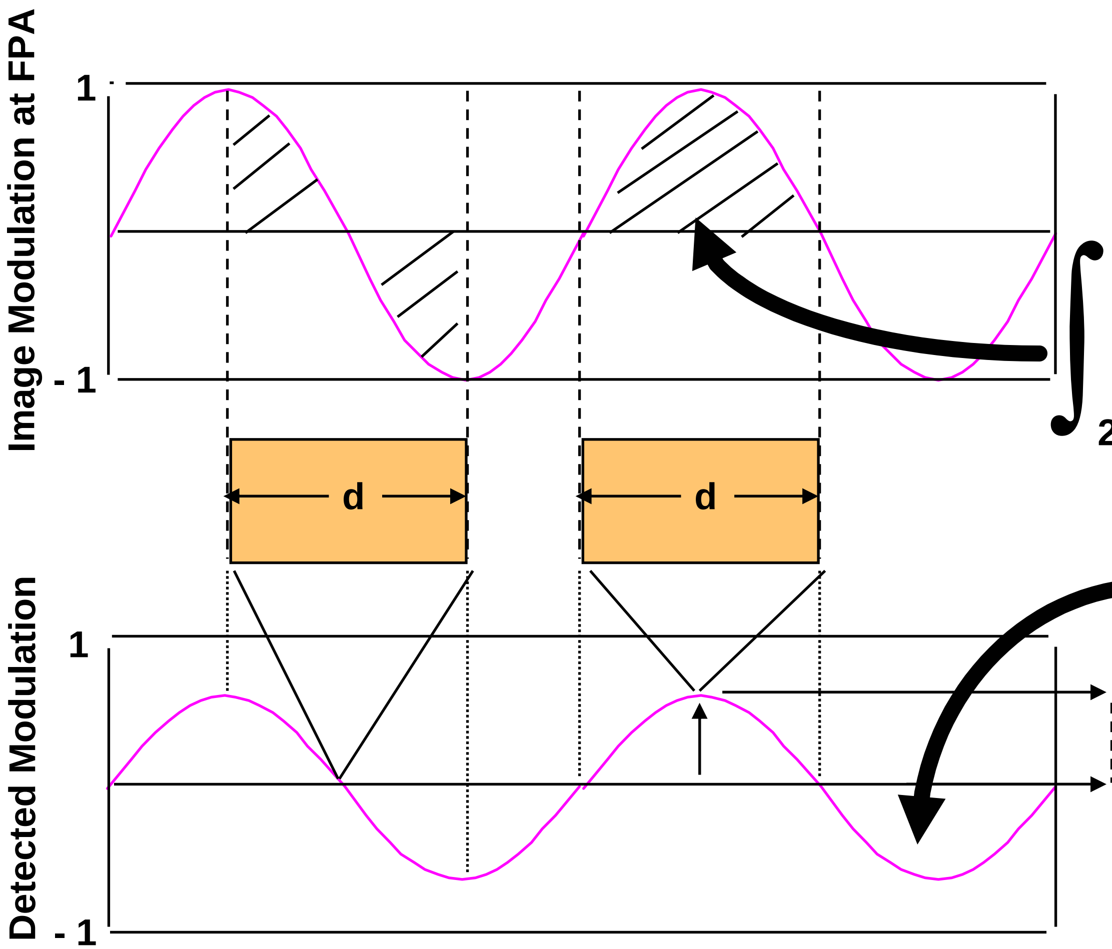
- **Sharp Cutoff More Difficult to Reproduce Than Smooth Fade**
- **Smooth Fade Does Not Contain "High Spatial Frequency" Intensity Variations - Less Affected by System Blur**

- **Any Function Can Be Represented by a Linear Summation of Pure Sinusoids**
- **The Smooth Fade *Contains* Fewer High Frequency Sinusoids Than the Sharp Cutoff**

Sine Wave Response is Modulation Transfer Function (MTF)

Santa Barbara Remote Sensing

Transfer of Scene Sine-Wave Modulation through System to Image



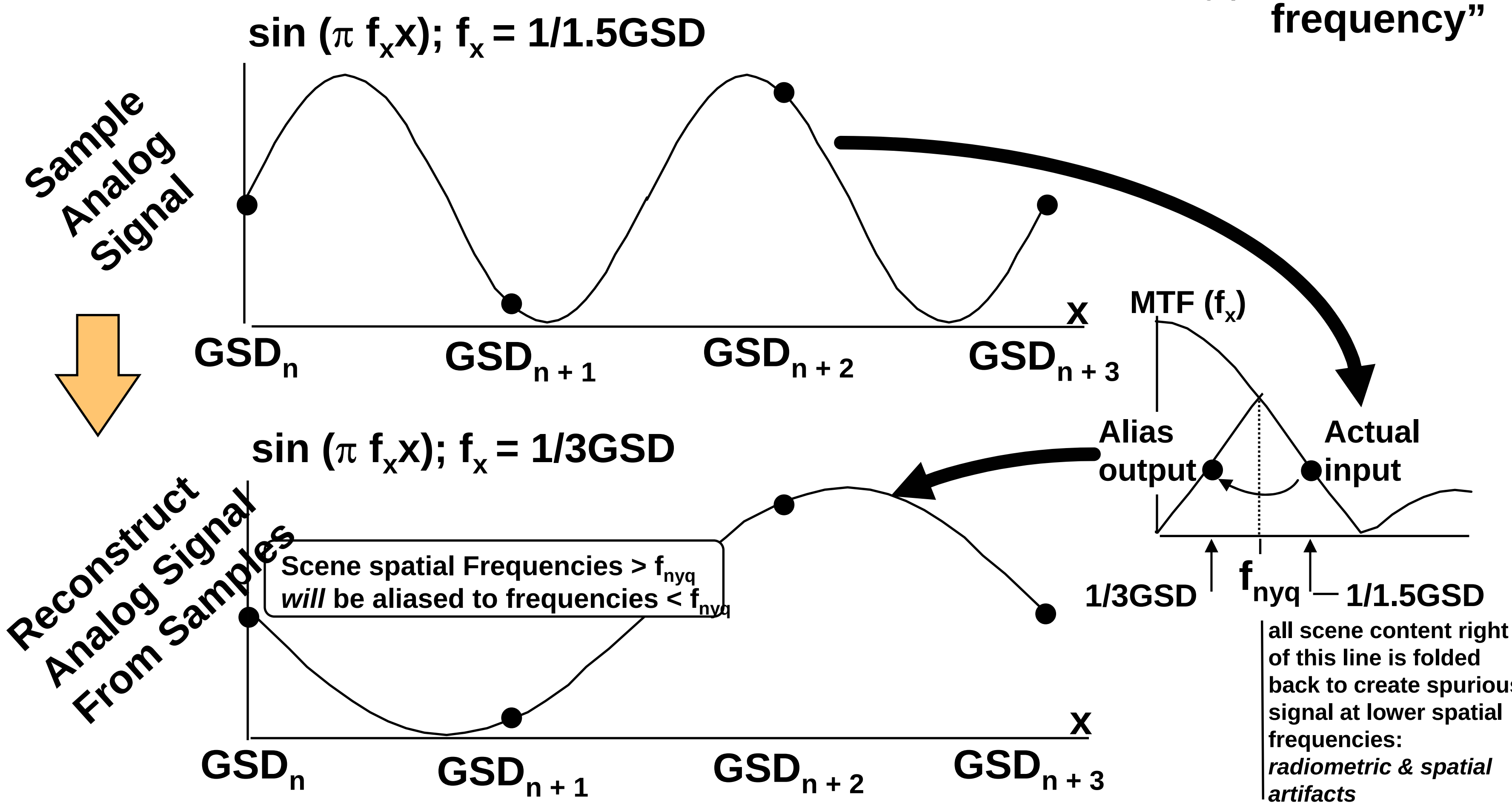
$$\int_{2n}^{2n+1} \sin \pi x \, dx = - \frac{\cos \pi x}{\pi} \Big|_{2n}^{2n+1} = 2 / \pi = 0.637$$

Spatial frequency $f_x = 1/2d$
Detector element = d

$$\mathrm{sinc}\,(f_x d) = \frac{\sin\,(\pi f_x d)}{\pi f_x d} = 2 / \pi = 0.637$$

Sampling Causes "Aliasing" Error

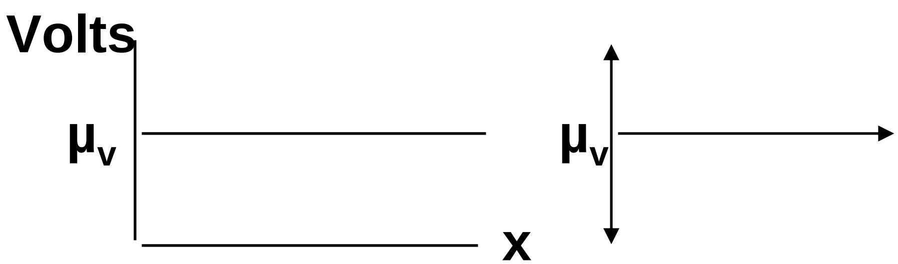
- GSD defines "Nyquist Sampling Rate" $f_x = f_{nyq} = 1/2GSD$
- Consider Image Sine Wave component at $f_x = 1/1.5GSD > f_{nyq}$: "folding frequency"



Radiometric Resolution is Limited by Noise

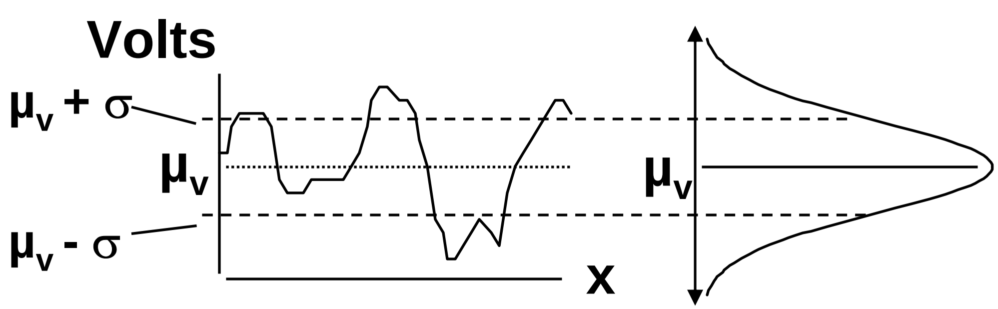
Raytheon
Santa Barbara Remote Sensing

- Consider Sensor Response to a Constant Radiance Input
- If We Could Obtain a Signal Like This:



Output Histogram: $P(\mu_v) = 1$

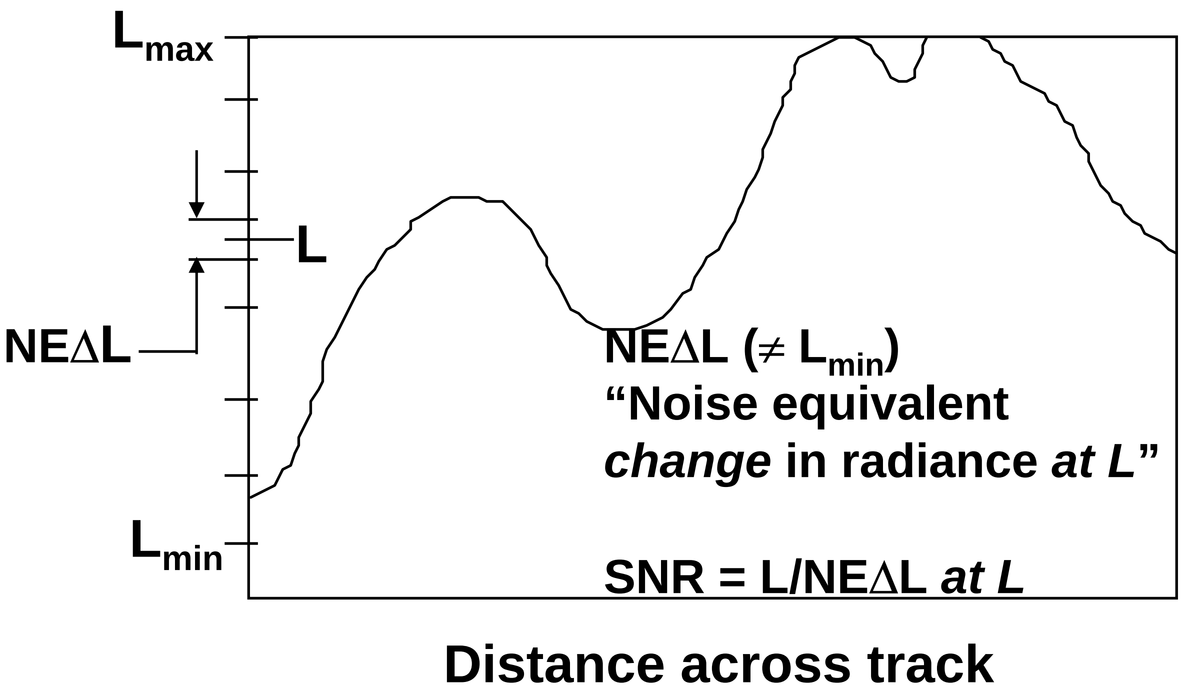
- Then Radiometric sensitivity would be unlimited
- Of course, that is impossible. Signal is more like this:



- Output Histogram ~ Gaussian
  $P(\mu_v - \sigma < \text{Volts} < \mu_v + \sigma) \sim 67\%$
- Maximize Signal-to-Noise Ratio:
  $SNR = \mu_v / \sigma$

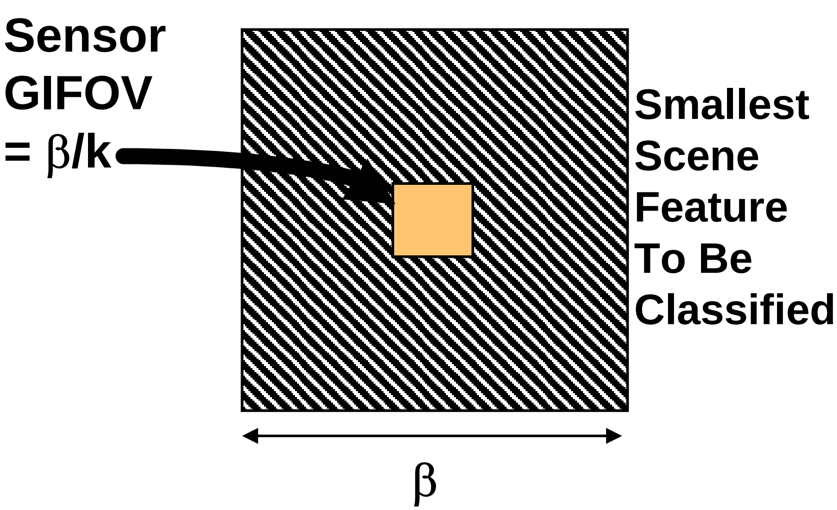
Signal to Noise Ratio = L/NEΔL

Raytheon
Santa Barbara Remote Sensing



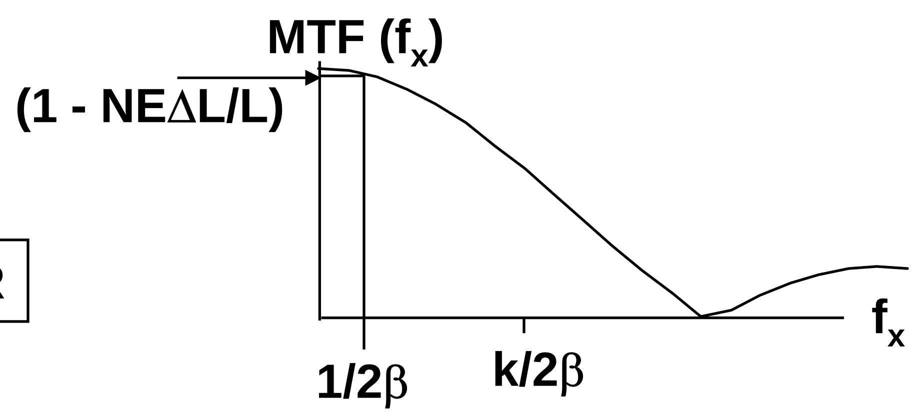
Design Challenge: Optimize MTF & SNR to Features

Raytheon
Santa Barbara Remote Sensing



Want smallest k (largest GIFOV) to match SNR (L/NEΔL):

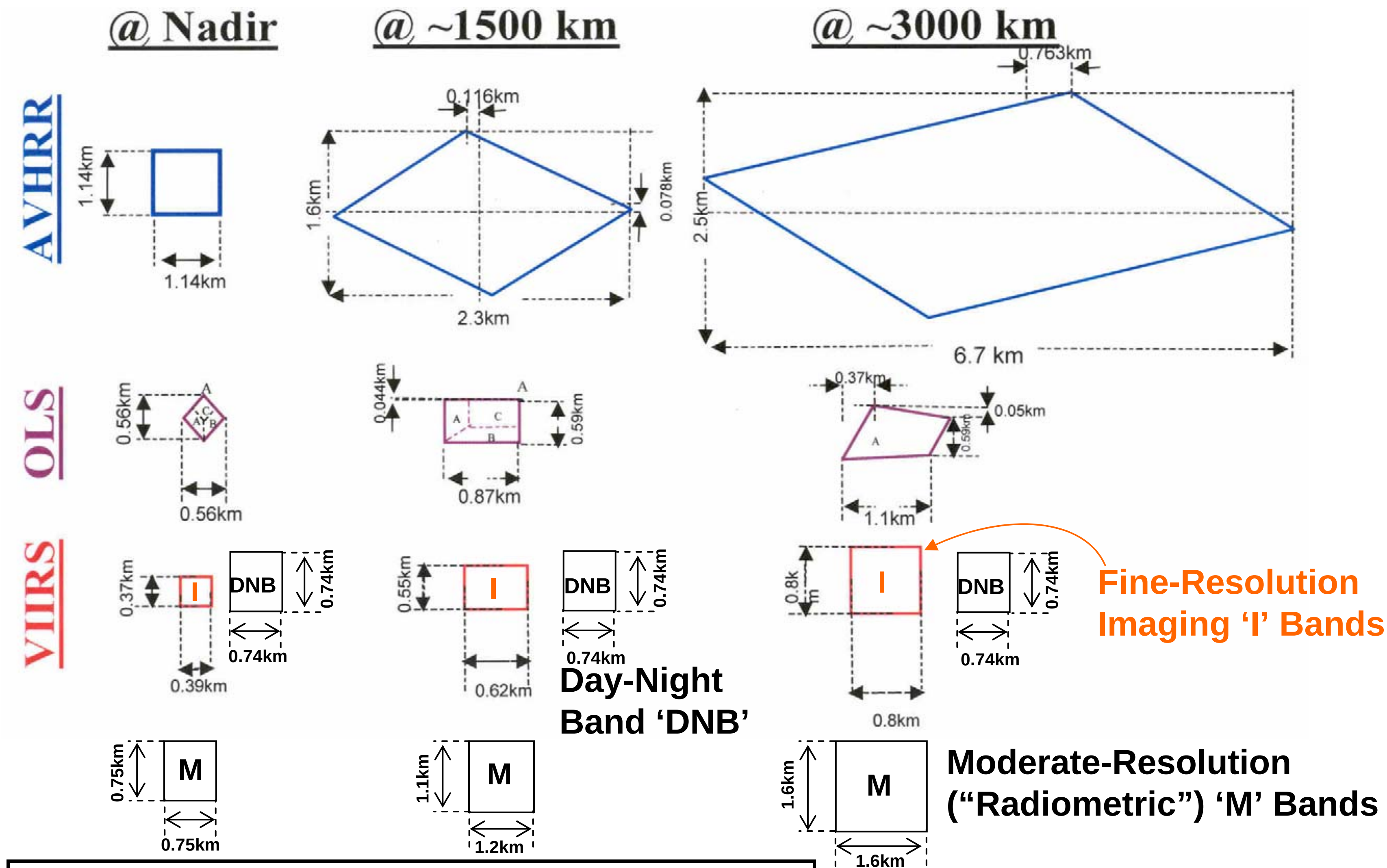
1. Radiometric Precision Error (NEΔL/L) ~ Allowable MTF Reduction at $f_x = 1/2\beta$
2. Select k so that sensor MTF > allowable value at $f_x = 1/2\beta$



Want Small GIFOV and High SNR

Finer Sampling, Spatial Resolution & Better Sensitivity

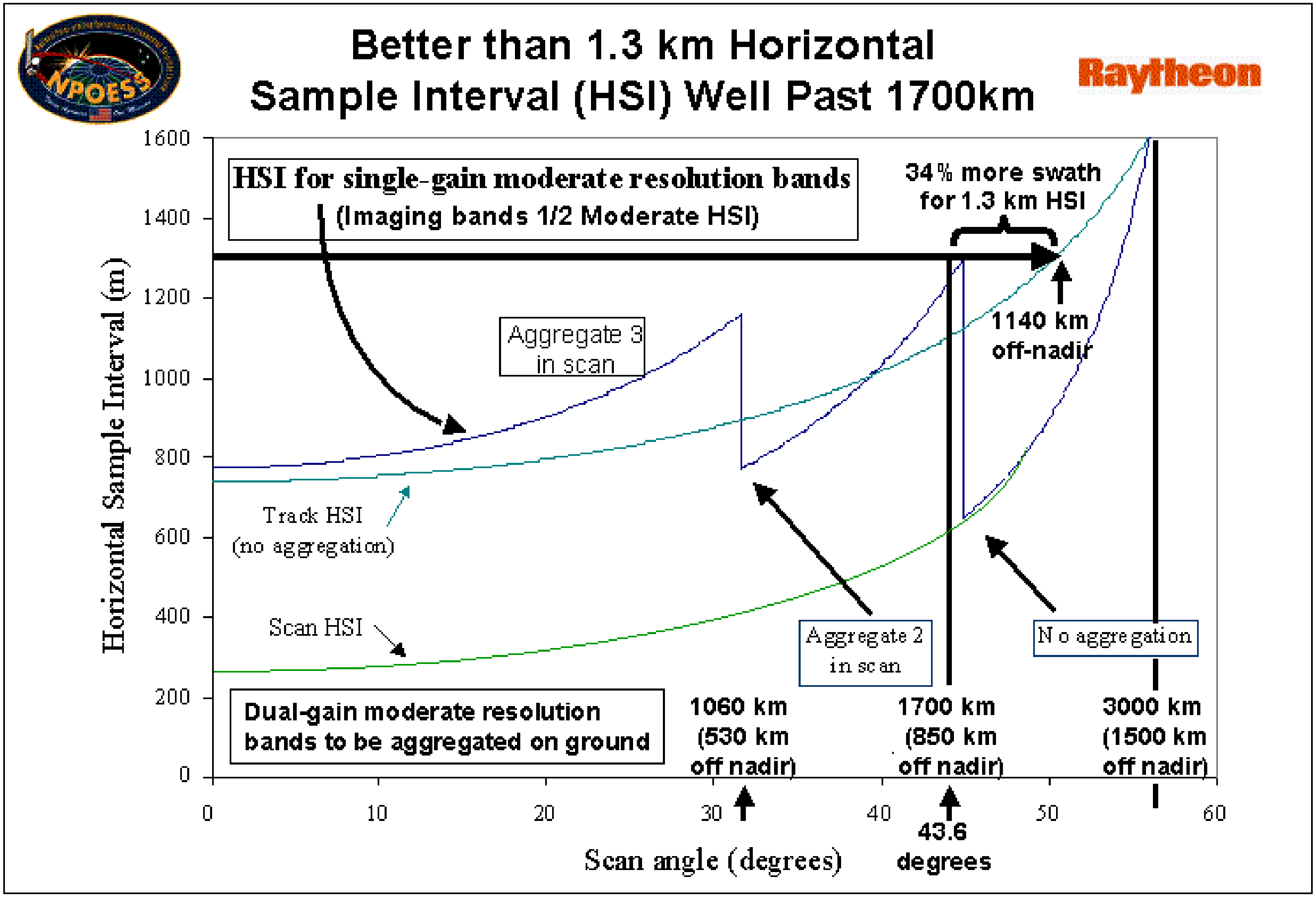
Raytheon
Santa Barbara Remote Sensing



SNR predicted and specified at worst-case edge of scan:
~60% better nadir SNR *and* finer spatial resolution

VIIRS Scan Geometry:
How will image look nadir vs. Edge?

Raytheon
Santa Barbara Remote Sensing



VIIRS Dramatically Improves Edge-of-Scan (EOS) Imagery

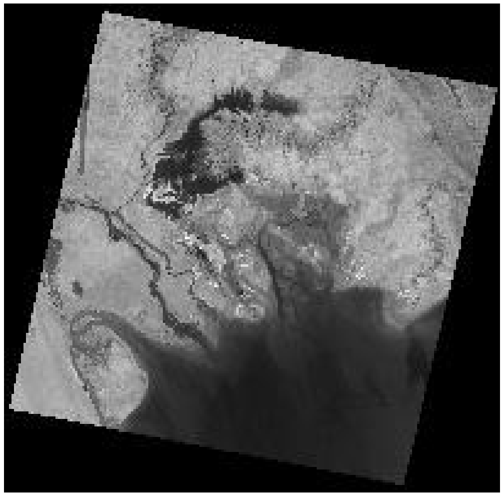
Raytheon

Santa Barbara Remote Sensing

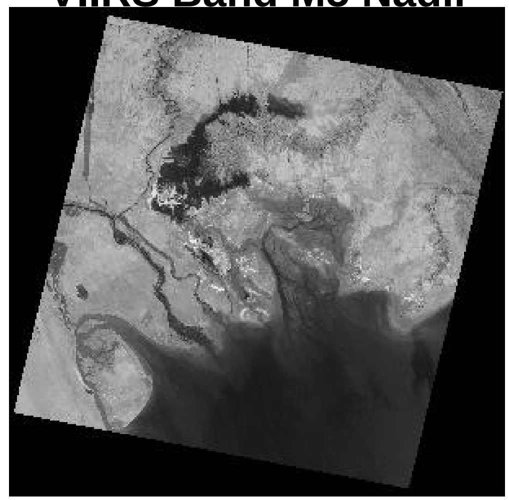
Nadir

Edge of Scan

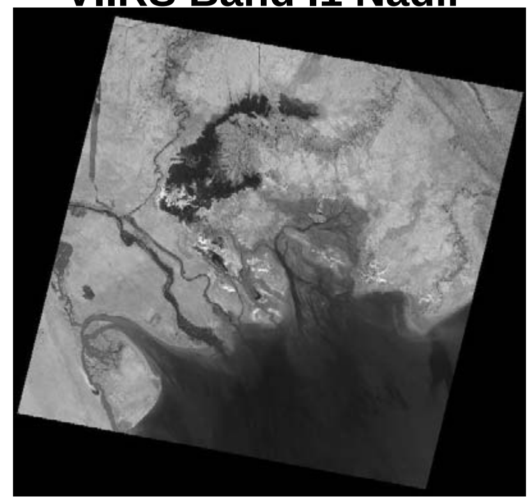
AVHRR Channel 1 Nadir



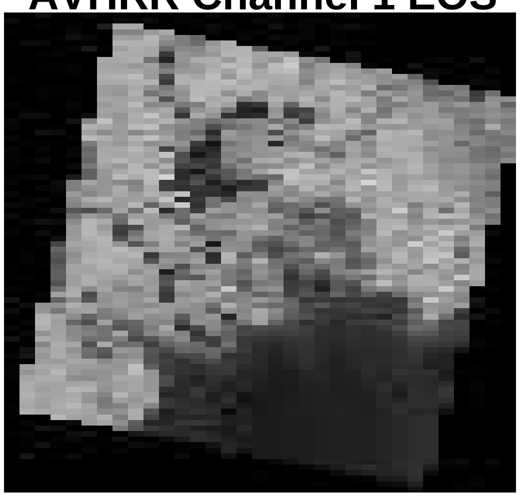
VIIRS Band M5 Nadir



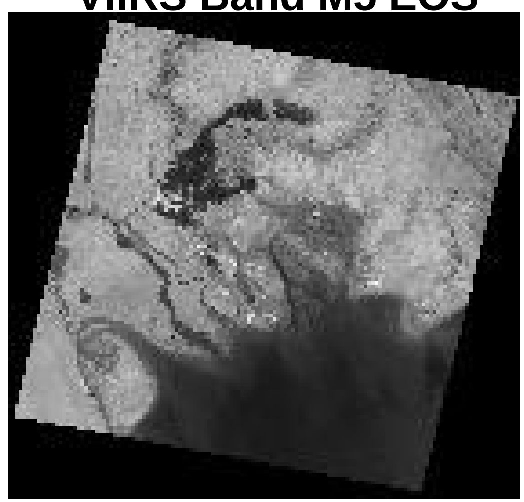
VIIRS Band I1 Nadir



AVHRR Channel 1 EOS



VIIRS Band M5 EOS



VIIRS Band I1 EOS